

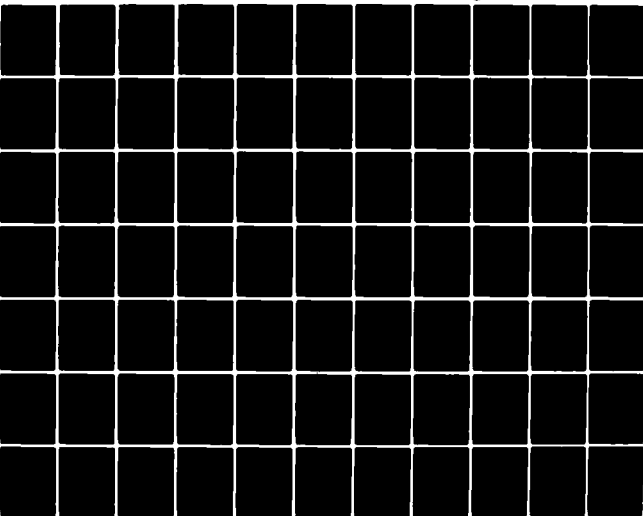
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LEVEL II

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(6) COMPUTER SIMULATION OF A SOLAR
ENERGY SYSTEM WHICH UTILIZES
FLAT-PLATE SOLAR COLLECTORS •

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COMPUTER SIMULATION OF A
SOLAR ENERGY SYSTEM WHICH
UTILIZES FLAT-PLATE SOLAR COLLECTORS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
Barry E. Prins
Captain USAF
Graduate Aeronautical Engineering
December 1979

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Preface

The past year of studying and programing equations for flat-plate solar collectors has culminated in this thesis. In it you will find an explanation of where the equations came from and a cost analysis, as well as instructions on how to operate the program. This program is set up in such a way that it can be used as an instructional aid for a solar energy course. The program has many parameters that must be input which allows the program operator the flexibility of changing or maintaining values of any parameters to observe the effect on the entire system.

I express my appreciation especially to Dr. James Hitchcock, my study advisor, for his tutoring and direction and his willingness to advise my efforts. Without him, none of this would have been completed.

Barry E. Prins

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List of Symbols

<u>English Symbols</u>	<u>Quantity</u>	<u>Units</u>
AC	Area of Collector surface	ft ²
AMIR	Annual mortgage interest rate	percent/100
AREA	Surface area of storage tank	ft ²
AREACST	Area dependent costs	\$/ft ²
ARINCST	Area independent costs	\$
BUEFF	Efficiency of backup heater	percent/100
BUFCOST	Cost of fuel for backup heater	\$/million BTU
C	Fraction of the time that the ground is covered by at least one inch of snow	percent/100
CN	Number of covers on the collector	dimensionless
Cp	Specific heat of collector fluid	BTU/lb-°F
CPS	Specific heat of storage fluid	BTU/lb-°F
d	Discount rate	percent/100
D	Daily diffuse radiation	BTU/hr-ft ²
\bar{D}	Monthly average daily diffuse radiation	BTU/hr-ft ²
DF	Dirt factor	dimensionless
DNPMT	Down payment	percent/100
EFF	Efficiency of heat exchanger	percent/100
EXTINS	Extra insurance and maintenance costs, as a fraction of initial cost	percent/100

<u>English Symbols</u>	<u>Quantity</u>	<u>Units</u>
FR	Heat removal efficiency of collector	percent/100
G	Mass flow rate of collector fluid divided by the surface area of the collector	lb/hr-ft ²
GG	Present value of payments on a one dollar loan	dimensionless
H	Daily total radiation on a horizontal surface	BTU/hr-ft ²
\bar{H}	Monthly average daily total radiation on a horizontal surface	BTU/hr-ft ²
H ₀	Daily total extraterrestrial radiation on a horizontal surface	BTU/hr-ft ²
Hh	Present value of all interest paid on a one dollar loan	dimensionless
HL	Hourly load on water heater	gallons
i	Inflation rate	percent/100
I _C	Instantaneous critical radiation intensity	BTU/hr-ft ²
II	Life cycle capital cost, as a fraction of initial cost	dimensionless
I _{Tt}	Instantaneous total radiation on a tilted surface	BTU/hr-ft ²
\bar{I}_{Tt}	Monthly average instantaneous total radiation on a tilted surface	BTU/hr-ft ²
JJ	Life cycle cost for extra insurance and maintenance as a fraction of investment	percent/100
k	Conductivity of insulating material	BTU/hr-ft ² -°F/in

<u>English Symbols</u>	<u>Quantity</u>	<u>Units</u>
K	Extinction coefficient of cover- material	inch ⁻¹
KK	Life cycle property tax rate, as a fraction of the initial cost	dimensionless
K_T	Daily clearness index	dimensionless
\bar{K}_T	Long term clearness index	dimensionless
L	Load on storage tank	BTU
$MASS$	Amount of fluid in storage	gallons
n	Day of the year	dimensionless
N	Number of years of the life cycle cost analysis	dimensionless
OO	Total life cycle cost, as fraction of initial cost	dimensionless
Q	Heat transfer	BTU/hr
R	Ratio of total radiation on a tilted surface to total radiation on a horizontal surface	dimensionless
\bar{R}	Monthly average ratio of total radiation on a tilted surface to total radiation on a horizontal surface	dimensionless
R_d	Ratio of direct radiation on a tilted surface to direct radiation on a horizontal surface	dimensionless
r_d	Ratio of hourly diffuse radiation on a horizontal surface to daily diffuse radiation on a horizontal surface	hour/day

<u>English Symbols</u>	<u>Quantity</u>	<u>Units</u>
r_t	Ratio of hourly total radiation on a horizontal surface to daily total radiation on a horizontal surface	hour/day
R2	Percentage of energy supplied by solar	percent/100
R3	Total investment in solar	\$
R4	First year fuel expense	\$
S	Slope of the collector from horizontal	degrees
SF	Shade factor	dimensionless
T	Temperature of storage fluid	degrees F
TAXBRKT	Effective income tax bracket	percent/100
TAXRT	Property tax rate, as a fraction of initial cost	percent/100
t_c	Thickness of collector cover material	inch
thc	Thickness of insulation around storage tank	inches
TLOAD	Yearly load on system	BTU
t_o	Monthly average daytime ambient temperature	degrees F
U	Collector heat loss coefficient	BTU/hr-ft ² -°F
UA	Heat loss coefficient-area	BTU/hr-°F
UT	Utilizability	percent/100

<u>Greek Symbol</u>	<u>Quantity</u>	<u>Units</u>
α	Absorptance	dimensionless
γ	Collector azimuth angle	degrees
δ	Declination	degrees
n_c	Index of refraction of cover material	dimensionless
θ	Angle between collector surface normal and sun's rays within cover material	degrees
θ_t	Angle between collector surface normal and sun's rays	degrees
θ_z	Solar zenith angle	degrees
ρ	Reflectivity of cover material	dimensionless
ρ_g	Ground reflectance	dimensionless
τ	Transmittance	dimensionless
$\tau\alpha$	Transmittance-absorptance product, accounting for reflected radiation	dimensionless
$(\tau\alpha)$	Transmittance-absorptance product, accounting for heat loss due to absorption	dimensionless
$(\overline{\tau\alpha})$	Effective transmittance-absorptance product	dimensionless
ϕ	Latitude	degrees
ω	Hour angle	degrees
ω_S	Sunset hour angle for a horizontal surface	degrees
ω_{SR}	Sunrise hour angle for a tilted surface	degrees
ω_{SS}	Sunset hour angle for a tilted surface	degrees

Abstract

This thesis is a computer simulation of a solar energy system that utilizes flat-plate solar collectors. By using available data from the U.S. Weather Bureau, the location and orientation of the collector, characteristics of the collector, and the type of storage and back-up heat system in use, it is possible to find the amount of solar energy collected and transferred to storage. A life cycle cost analysis can be accomplished by using financial data and an inflation-discount function to reduce all costs to present year dollars. By varying any of a number of parameters the operator can determine what effect it has on the amount of energy collected and the life cycle costs. Results of running the program for a solar water heater system indicate that such a system is cost effective, when compared to a gas water heater system, only when the federal and state tax incentives were taken into account. However, electricity is approximately three times as expensive as gas per BTU of energy gained so the solar energy system is economically feasible when compared to an electric water heating system.

COMPUTER SIMULATION OF A SOLAR ENERGY SYSTEM WHICH UTILIZES FLAT-PLATE SOLAR COLLECTORS

I Introduction

Background

Solar energy is a growing field of study, especially since the oil embargo of 1973. With gas lines and steadily rising prices for petroleum products, and the continued need for a clean environment, it is becoming apparent to more Americans that non-fossil fuels must be utilized to decrease our dependence on foreign oil and maintain a clean environment. Solar energy is one type of energy that is clean and available worldwide. With the rising prices of petroleum products, solar energy becomes more and more economically attractive.

Purpose

The purpose of this study was to write a computer program to simulate a solar energy system that utilizes a fixed flat-plate solar collector. The program is flexible enough to allow for several different types of storage and energy transfer options, the types of systems that would be used in a residence. A cost analysis is included so that the amount of money saved can be calculated. The program is designed for use as an instructional aid for a solar

energy course. The student is able to vary any of a number of parameters to see what effect each has on the amount of useful energy collected.

Scope

This program is limited to fixed flat-plate solar collectors for several reasons. The flat-plate solar collector has considerable operating experience, is less expensive, and is less complex than concentrating collectors so it would be more likely to be used in a residence.

The program has three types of storage and energy transfer at present. One is a simple system that uses water as the collector fluid and as the storage fluid and uses only one tank with no auxiliary heating, Fig 1. In this type system, hot water is used only after the sun has heated it.

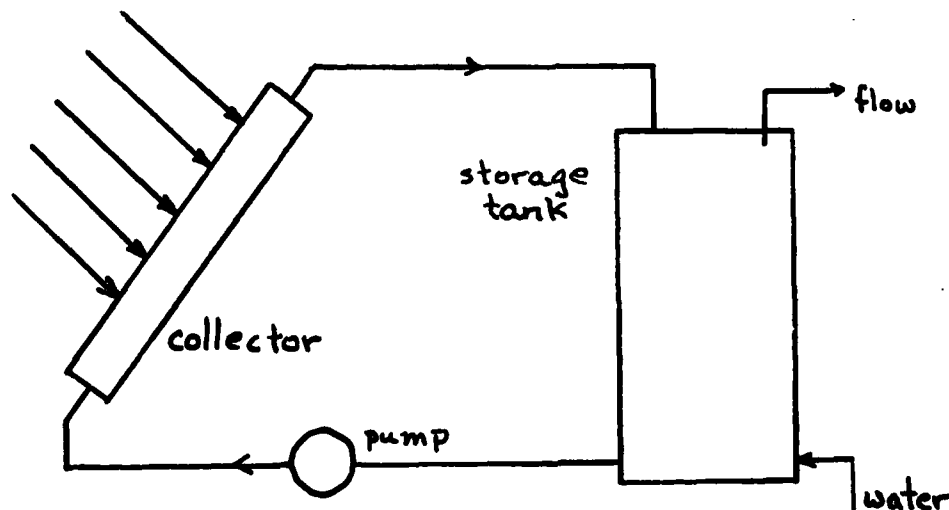


Fig 1. System 1

The second system uses water for both the collector and storage fluids. It differs from system 1 in that it has a storage tank and a conventional water heater, Fig 2. The solar energy is used to heat the water in the storage tank which in turn feeds into the conventional water heater. This allows the water heater to draw its supply from the hot water in the storage tank instead of from the outside water source.

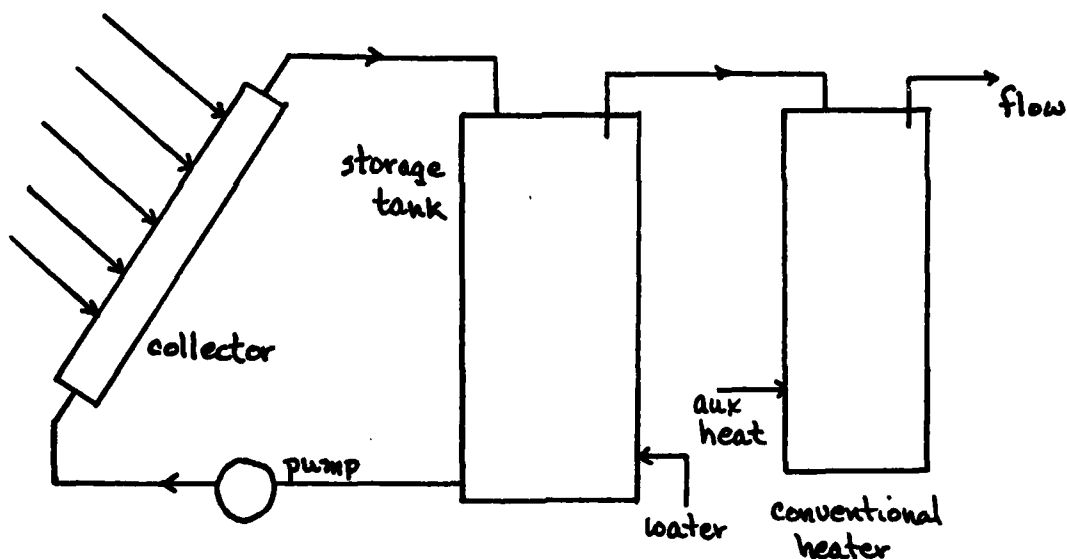


Fig 2. System 2

The third system is the same as system 2 with the exception of the collector fluid. In this system an anti-freeze type solution is used as the collector fluid and is passed through a heat exchanger to transfer the energy to the water in the storage tank. Fig 3.

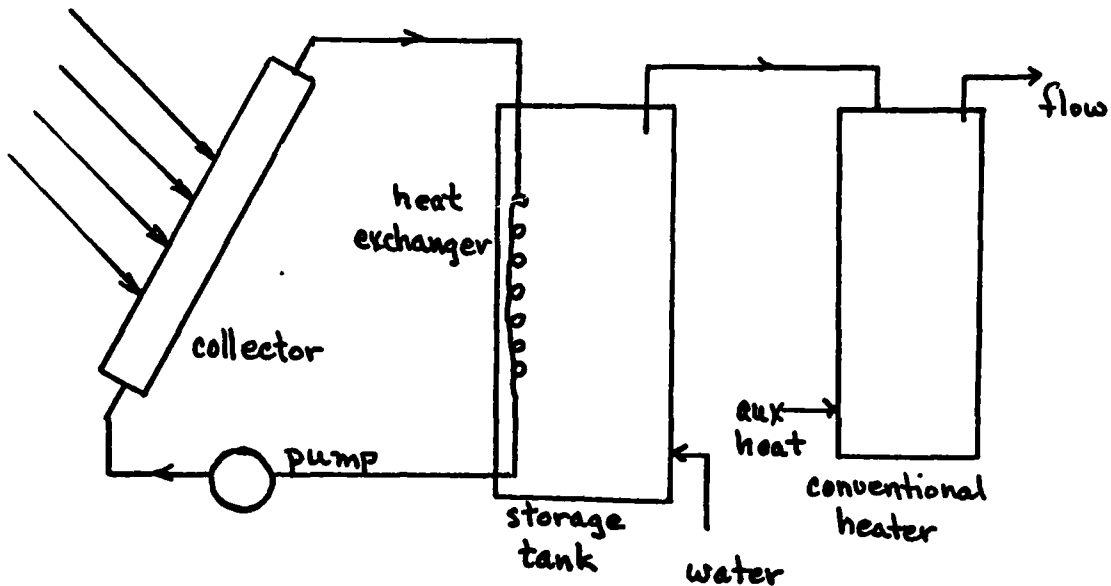


Fig 3. System 3

Additional systems can be added at a later date.

Appendix A consists of step by step instructions for using the program, and a list of the input data cards is contained in Appendix B.

Appendix A and Appendix B are written so that they can be extracted from the study and used with the computer program as a self-contained package. Consequently, there is some repetition between the main body and the appendices.

II The System Model

This section contains the equations that are used to determine the amount of useful energy collected. Unless otherwise referenced, these equations were used in the works of Liu and Jordan (Ref 8 and Ref 9).

Collection Equations

Since the 1950's, much solar data has been collected around the world. The U.S. Weather Bureau collects data in almost 80 cities across the country using horizontally positioned pyrometers. Three items for each month, in each of 80 cities in the United States and Canada are tabulated in Ref 9: the monthly average daily total radiation on a horizontal surface (\bar{H}); the monthly average daytime ambient temperature (t_o); and the long-term average clearness index (\bar{K}_T). Using these values and known values of the orientation and location of the collector, it is possible to find the amount of radiant energy that reaches the collector.

Once the energy reaching the collector is known, it is combined with specific values of the collector characteristics to find the useful energy collected. This is then combined with properties of the energy transfer and storage system to determine the amount of energy actually stored. By combining the energy actually stored, the heating load,

the costs for the solar energy system, and the cost for a conventional heating system, it is possible to determine the amount of money saved by using the solar energy system.

The amount of energy that reaches the collector is a function of the orientation of the collector relative to the Earth, the position of the Earth relative to the sun, and the effects of the atmosphere on the radiation.

The declination (δ) is the angular position of the sun at solar noon with respect to the plane of the Earth's equator, with angles north of the equator positive. It can be determined by the approximate equation:

$$\delta = 23.45 \times \sin \left(2\pi \times \frac{284 + n}{365} \right) \quad (1)$$

where n is the day of the year (i.e., on January 1, $n = 1$ and on December 31, $n = 365$).

The sunset hour angle for a horizontal surface (ω_s), measured from solar noon, is given by the equation:

$$\omega_s = \arcsin (-\tan \phi \times \tan \delta) \quad (2)$$

where ϕ is the latitude of the collector, north positive.

For a horizontal collector and for a tilted collector facing due south, the sunrise and sunset hour angles are the same magnitude. The sunset hour angle is measured as positive and the sunrise hour angle is measured as negative.

If the tilted collector is not facing due south, then the sunrise and sunset hour angles are not the same magnitude. If the collector is facing east of due south (i.e., $\gamma < 0$) then the following equations apply for the sunrise (ω_{sr}) and sunset (ω_{ss}) hour angles (Ref 7):

$$\omega_{sr} = - \text{minimum} \{ \omega_s, \cos^{-1} [(AB + \sqrt{A^2 - B^2 + 1}) / (A^2 + 1)] \} \quad (2a)$$

$$\omega_{ss} = \text{minimum} \{ \omega_s, \cos^{-1} [(AB - \sqrt{A^2 + B^2 + 1}) / (A^2 + 1)] \} \quad (2b)$$

If the collector is facing west of due south (i.e., $\gamma > 0$) then the sunset and sunrise hour angles are given by the equations:

$$\omega_{sr} = - \text{minimum} \{ \omega_s, \cos^{-1} [(AB - \sqrt{A^2 + B^2 + 1}) / (A^2 + 1)] \} \quad (2c)$$

$$\omega_{ss} = \text{minimum} \{ \omega_s, \cos^{-1} [(AB + \sqrt{A^2 + B^2 + 1}) / (A^2 + 1)] \} \quad (2d)$$

$$\text{where } A = \frac{\cos \phi}{\sin \gamma \tan s} + \frac{\sin \phi}{\tan \gamma} \quad (2e)$$

$$B = \tan \delta \left[\frac{\cos \phi}{\tan \gamma} - \frac{\sin \phi}{\sin \gamma \tan S} \right] \quad (2f)$$

By comparing the hour angle to the sunrise and sunset hour angles it is possible to determine if the sun is above the horizon and in front of the collector. If the sun is in front of the collector and above the horizon then solar energy will be collected.

The long-term clearness index (\bar{K}_T) is the fraction of the extraterrestrial radiation on a horizontal surface that is transmitted through the atmosphere. It is a function of cloudiness, humidity, air pollution and suspended particulate matter. Generally, the long-term clearness index for a given locality is between .3 and .75. Most localities are close enough to one of the U.S. Weather Bureau reporting stations to use the measured values of \bar{H} . The long-term clearness index can be determined by using the equation:

$$\bar{K}_T = \frac{\bar{H}}{H_0} \quad (3)$$

where H_0 is the extraterrestrial radiation on a horizontal surface and is given by the equation:

$$H_0 = \frac{24}{\pi} \times 432 \times (1 + .033 \times \cos \frac{2\pi n}{365}) \times (\cos \delta \cos \phi \sin \omega_s + \sin \phi \sin \delta) \quad (4)$$

where 432 is the solar constant in BTU/hr - sq. ft.

Using experimental data, Liu and Jordan (Ref 8) have shown that the ratio of the monthly average daily diffuse radiation to monthly average daily total radiation ($\frac{\bar{D}}{\bar{H}}$) is a function of the monthly average long-term clearness index. They plotted a curve through the data points but gave no formula for the curve. It was found that using the following equations results in a close approximation of the curve.

$$\frac{\bar{D}}{\bar{H}} = 1.2 - 2.0 \bar{K}_T, \text{ if } \bar{K}_T < .35 \quad (5)$$

$$\frac{\bar{D}}{\bar{H}} = .79 - .83 \bar{K}_T \geq .35$$

These equations show that for smaller values of \bar{K}_T , a greater percentage of the radiation is diffuse because there are more particles in the air to absorb and scatter the radiation.

The angle between the collector surface normal and the Sun's rays is found by the equation:

$$\begin{aligned} \cos \theta_t = & \sin \delta \sin \phi \cos S - \sin \delta \cos \phi \sin S \cos \gamma \\ & + \cos \delta \cos \phi \cos \omega \cos S \\ & + \cos \delta \sin \phi \cos \omega \sin S \cos \alpha \\ & + \cos \delta \sin S \sin \gamma \sin \omega \end{aligned} \quad (6)$$

where γ is the collector azimuth angle (i.e., the angle between the collector surface normal and the local meridian), with angles to the west measured positive, and ω is the hour angle measured from solar noon with afternoon hours positive (one hour = 15 degrees = .2618 radians), and S is the slope of the collector, from horizontal.

The solar zenith angle (i.e., the angle between the Sun's rays and the local vertical) is given by the equation:

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (7)$$

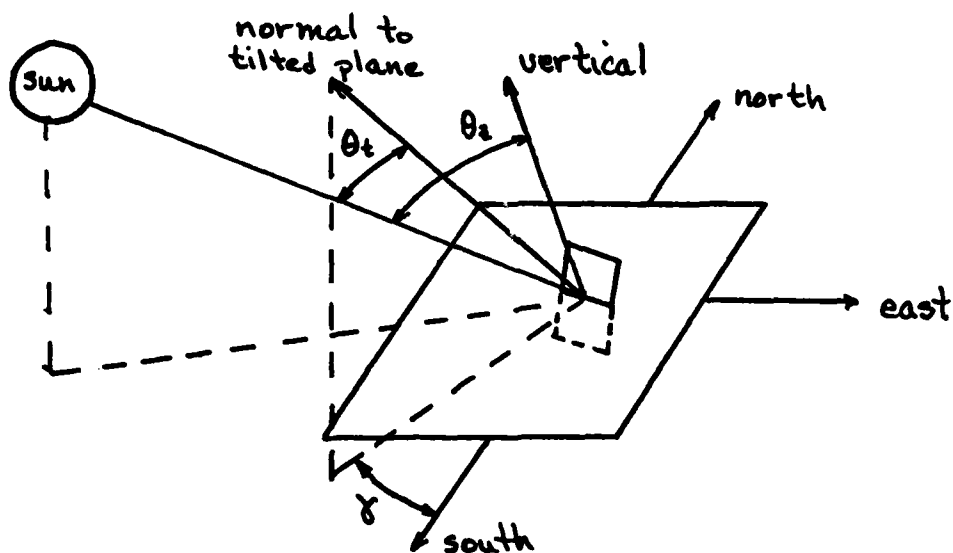


Fig 4. Diagram of θ_t and θ_z

The total radiation reaching the collector is the sum of the direct radiation, the diffuse sky radiation and the diffuse radiation reflected from the ground.

To find the ratio of direct radiation on a tilted surface to direct radiation on a horizontal surface use the equation:

$$R_b = \frac{\cos \theta_t}{\cos \theta_z} \quad (8)$$

The conversion factor to find the diffuse sky radiation, assuming uniform intensity, is $\frac{1}{2} (1 + \cos S)$. The conversion factor to find the diffuse ground reflected radiation is $\frac{1}{2} (1 - \cos S) \rho_g$, ρ_g is the ground reflectance found from equation:

$$\rho_g = .2 + .5C \quad (9)$$

where C is the fraction of the time during the month where snow of greater than 1 inch thickness is present.

To convert these quantities from daily to hourly values two more equations are needed. The ratio of hourly diffuse radiation on a horizontal surface to daily diffuse radiation on a horizontal surface is given by the equation:

$$r_d = \frac{\pi}{24} \times \frac{(\cos \omega - \cos \omega_s)}{(\sin \omega_s - \omega_s \cos \omega_s)} \quad (10)$$

The ratio of hourly total radiation on a horizontal surface to daily total radiation on a horizontal surface (r_t) is also given by equation (10). Whillier (Ref 11) and Hottel and Whillier (Ref 5) have shown that the experimentally obtained ratios r_t are different than those computed by equation (10). However, modifying the equation by shifting the curves six degrees (.1047 radians) results in a more accurate approximation. The equation then becomes:

$$r_t = \frac{\pi}{24} \times \frac{(\cos \omega - \cos (\omega_s - .1047))}{(\sin (\omega_s - .1047) - (\omega_s - .1047) \cos (\omega_s - .1047))} \quad (11)$$

Combining these factors it is possible to find the monthly average ratio of total radiation on a tilted surface to total radiation on a horizontal surface by using the equation of Liu and Jordan (Ref 9):

$$\bar{R} = (1 - \frac{r_d}{r_t} \frac{\bar{D}}{\bar{H}}) R_b + \frac{1}{2} (1 + \cos S) \frac{r_d}{r_t} \frac{\bar{D}}{\bar{H}} + \frac{1}{2} (1 - \cos S) \rho_g \quad (12)$$

Using this value it is now possible to find the monthly average instantaneous total radiation on a tilted surface by:

$$\bar{I}_{T_t} = \bar{R} r_t \bar{H} \quad (13)$$

The amount of solar radiation that is actually collected is a function of the collector material, the number of covers on the collector, the ambient temperature, and the amount of radiation reaching the collector. Of the

radiation incident on the collector, some is reflected, some is absorbed by the cover material, and the rest is transmitted through the cover material. The radiation that is transmitted is refracted whenever the radiation strikes the cover obliquely.

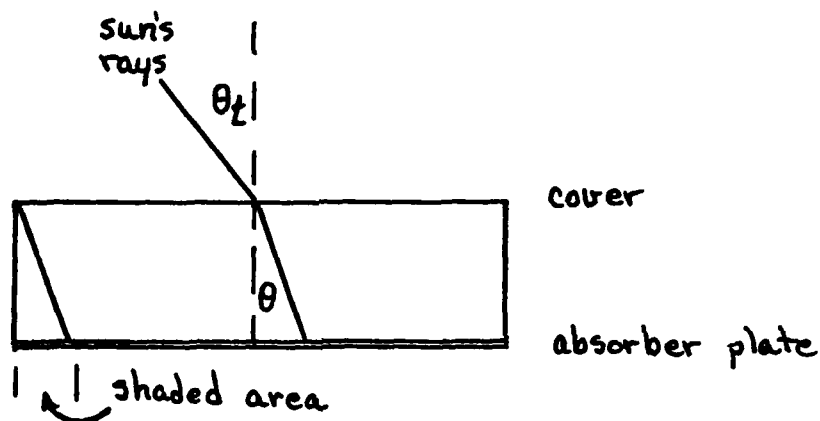


Fig 5. Diagram showing refraction and shading

The angle (θ) between the surface normal and the Sun's rays within the cover material is found using Snell's Law:

$$\sin \theta = \frac{\sin \theta_t}{\eta_c}, \text{ if } \theta_t \neq 0 \quad (14)$$

$$\theta = 0, \text{ if } \theta_t = 0 \quad (15)$$

where η_c is the index of refraction of the cover material.

The amount of radiation that reaches the absorber plate is a function of the number of covers and the transmittance of those covers. Some of the radiation that is transmitted through the first cover will be reflected back out by the second cover. Part of this reflected radiation is then re-reflected from the first cover back to the second cover as shown in Fig 6.

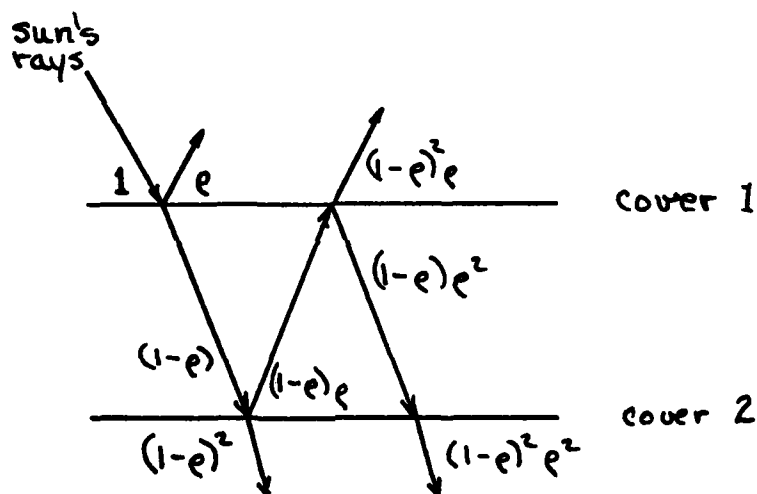


Fig 6. Diagram showing reflection in cover system

The transmittance for CN covers (CN is the number of covers), taking into account the radiation reflected, is given by the equation (Ref 4):

$$\tau_{r,CN} = \frac{1 - \rho}{1 + (2 \text{ CN} - 1) \rho} \quad (16)$$

where ρ is the reflectivity of the cover material. This relationship holds for each of the two components of unpolarized light. The transmittance, accounting for reflectance is found by taking the average of the two components. Fresnel has derived a relation for the reflectivity when unpolarized light passes from one medium to another that accounts for each of the components of polarized light:

$$\rho_1 = \frac{\sin^2 (\theta - \theta_t)}{\sin^2 (\theta + \theta_t)}, \quad \text{when } \theta_t > 0 \quad (17a)$$

$$\rho_2 = \frac{\tan^2 (\theta - \theta_t)}{\tan^2 (\theta + \theta_t)}, \quad \text{when } \theta_t > 0 \quad (17b)$$

To find the transmittance, equation (16) is solved first with $\rho = \rho_1$ and then with $\rho = \rho_2$ and the average value of the two is the transmittance, accounting for reflection. If $\theta_t = 0$, then the reflectivity is found by combining Fresnel's Law and Snell's Law, which results in:

$$\rho = \left[\frac{n_c - 1}{n_c + 1} \right]^2 \quad (18)$$

Each time the radiation strikes a cover, part of the radiation is absorbed by the cover material. The transmittance of CN covers, accounting for absorption, is given by the equation (Ref 4).

$$\tau_{a,CN} = e^{-K \times CN \times t_c / \cos \theta} \quad (19)$$

where K is the extinction coefficient of the cover material and t_c is the thickness of a cover. The total transmittance (τ_{CN}) is simply the product of the two (Ref 4).

$$\tau_{CN} = \tau_{r, CN} \times \tau_{a, CN} \quad (20)$$

This is a good equation as long as $K \times CN \times t_c / \cos \theta$ is small, which is met in solar collectors at angles of practical interest.

When the radiation reaches the absorber plate most is absorbed, however, some is reflected back to the cover system where some of this reflected radiation is absorbed by the cover material, some transmitted and some reflected back to the absorber plate. This is shown in Fig 7, where α is the absorptance of the absorber plate.

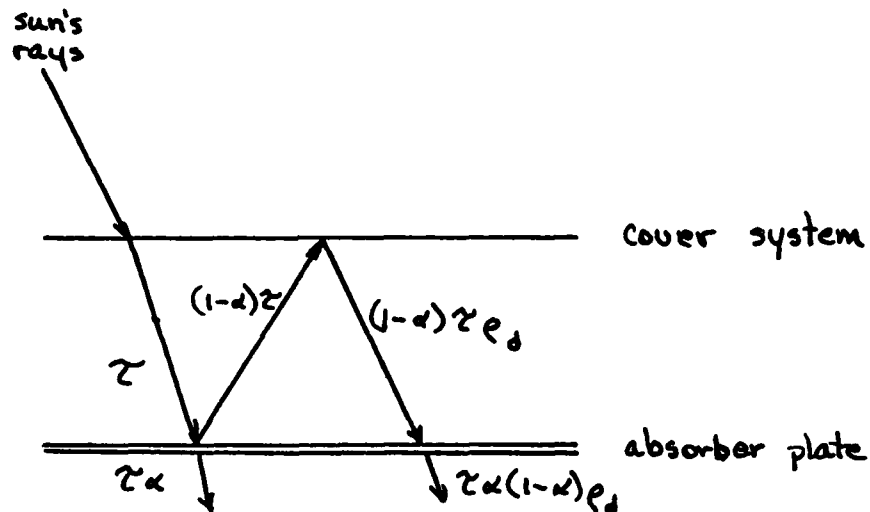


Fig 7. Diagram showing reflection and absorption of absorber plate

The transmittance - absorptance product that accounts for this reflected radiation is given by the equation (Ref 4):

$$\tau_{\alpha} = \frac{\tau_{CN} \alpha}{1 - (1 - \alpha) \rho_d} \quad (21)$$

where ρ_d is the diffuse reflectance of the cover system.

The absorptance of the absorber plate is dependent on the type of surface coating used and the angle of incidence. The manufacturer will list the normal incidence value of absorptance. Values as high as .98 are found when using special coatings designed for absorber plates. The values

are lower for larger angles of incidence. The values for α / α_n at angles of incidence from zero to 90 degrees can be approximated by the equation:

$$\frac{\alpha}{\alpha_n} = \cos^{.15} \theta_t \quad (22)$$

where α_n is the absorptance at normal incidence. This equation proved highly accurate for θ_t less than 60 degrees.

The transmittance-absorptance product that accounts for the reduction in heat loss due to absorption is found using the equation (Ref 4):

$$(\tau\alpha) = \tau\alpha + (1 + \tau_{a,CN}) \sum_1^{CN} a_i \tau_i - 1 \quad (23)$$

where a_i is the ratio of the overall loss coefficient to the loss coefficient of the i th cover to the surroundings. It is a function of the emittance of the absorber plate and the wind speed. For a wind speed of 5 meters/second and an emittance of .95 the a_i 's are: with one cover, $a_1 = .2$; with two covers, $a_1 = .15$ and $a_2 = .62$; with three covers, $a_1 = .14$, $a_2 = .45$, and $a_3 = .75$. (Ref 4)

There are two other factors involved in finding the effective transmittance-absorptance product. They are the shading factor and the dirt factor. The shading factor (SF)

is a fraction which shows how much of the absorber plate is shaded by the side of the collector whenever the angle of incidence is not normal to the collector. As shown in Fig 5, the shading factor is found by using the equation:

$$SF = \frac{CN}{48} \tan \theta \quad (24)$$

The dirt factor (DF) is a measure of the amount the radiation is reduced because of dirt on the cover. Unless a dirt factor is known from previous testing, a recommended value is .02.

Using the shading factor and the dirt factor it is possible to find the effective transmittance-absorptance product:

$$(\overline{\tau\alpha}) = .98 (1 - SF) (1 - DF) (\tau\alpha) \quad (25)$$

where .98 is a factor used by Liu and Jordan (Ref 9) to account for diffuse radiation, which is a small part of the total radiation.

The energy collected is a function of the effective radiation arriving at the absorber plate, the heat removal efficiency (FR) of the collector, and the utilizability. Utilizability is the name given by Hottel and Whillier (Ref 5) to the dimensionless efficiency factor that is the fraction of the incident radiation that can be collected, or utilized, by an idealized collector (i.e., one that has

$FR = 1$ and $(\overline{\tau\alpha}) = 1$. The utilizability is not 1 because of the heat loss through the sides, back and cover plates of the collector.

The critical radiation (I_c) is the irradiation at which energy is collected by and lost from the collector at the same rate. When this is known the collector system can be used effectively by having the collector fluid moving through the collector when it will collect energy (i.e., incident radiation greater than I_c) and not moving when it will give up energy. The ratio of critical radiation to monthly average instantaneous total radiation is given by the equation:

$$\frac{I_c}{\overline{I}_{Tt}} = \frac{U (t_1 - t_o)}{(\overline{\tau\alpha}) \overline{I}_{Tt}} \quad (26)$$

where U is the heat loss coefficient of the collector, t_1 is the temperature of the fluid entering the collector, and t_o is the average ambient air temperature.

Using the long term clearness index and the chart in Table 1, (Ref 8) it is possible to find the ratio of instantaneous radiation to monthly average instantaneous radiation on a tilted surface using the following equations:

$$\begin{aligned} \frac{D}{H} &= (2.32 K_T - 3.22) K_T^2 + 1, \text{ if } K_T < .75 \\ \frac{D}{H} &= .17, \text{ if } K_T \geq .75 \end{aligned} \quad (27)$$

$$R = \left[1 - \frac{r_d}{r_t} \frac{D}{H} \right] R_b + \frac{1}{2} (1 + \cos S) \frac{r_d}{r_t} \frac{D}{H} + \frac{1}{2} (1 + \cos S) \rho_g \quad (28)$$

$$\frac{I_{Tt}}{\bar{I}_{Tt}} = \frac{R}{\bar{R}} \frac{K_T}{\bar{K}_T} \quad (29)$$

Liu and Jordan (Ref 9) have shown that with statistical data, a curve can be plotted as in Fig 8, where the shaded area under the curve is the utilizability and is given by the equation:

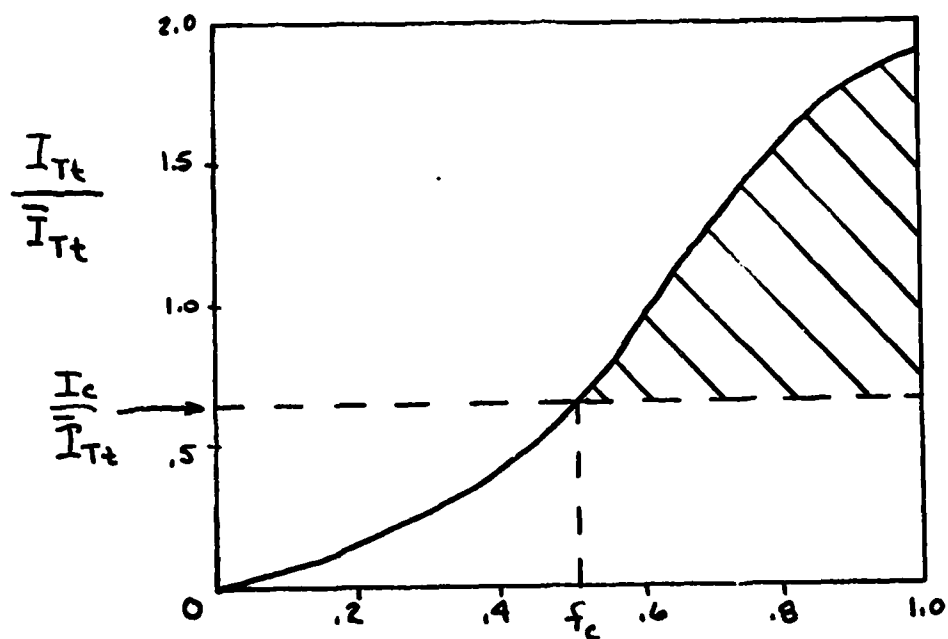
$$UT = \int_{f_c}^1 \left[\frac{I_{Tt}}{\bar{I}_{Tt}} - \frac{I_c}{\bar{I}_{Tt}} \right] df \quad (30)$$

The curve shown in Fig 8 is for one value of \bar{K}_T . There are a whole family of curves, one for each value of \bar{K}_T . The curves are valid for hourly and daily data. Liu and Jordan also showed that there are generalized K_T curves valid for monthly values. Fig 9 is a graphical representation of the values in Table 1.

Table 1. Generalized Monthly K_T Curve

Value of f

$K_T \backslash \bar{K}_T$.3	.4	.5	.6	.7
.04	.073	.015	.001	.000	.000
.08	.162	.070	.023	.008	.000
.12	.245	.129	.045	.021	.007
.16	.299	.190	.082	.039	.007
.20	.395	.249	.121	.053	.007
.24	.496	.298	.160	.076	.007
.28	.513	.346	.194	.101	.013
.32	.579	.379	.234	.126	.013
.36	.628	.438	.277	.152	.027
.40	.687	.493	.323	.191	.034
.44	.748	.545	.358	.235	.047
.48	.793	.601	.400	.269	.054
.52	.824	.654	.460	.310	.081
.56	.861	.719	.509	.360	.128
.60	.904	.760	.614	.410	.161
.64	.936	.827	.703	.467	.228
.68	.953	.888	.792	.538	.295
.72	.967	.931	.873	.648	.517
.76	.979	.967	.945	.758	.678
.80	.986	.981	.980	.884	.859
.84	.993	.997	.993	.945	.940
.88	.995	.999	1.000	.985	.980
.92	.998	.999		.996	1.000
.96	.998	1.000		.999	
1.00	1.000			1.000	



f - fractional time during which radiation $< \bar{I}_{Tt}$

Fig 8. Sample radiation distribution

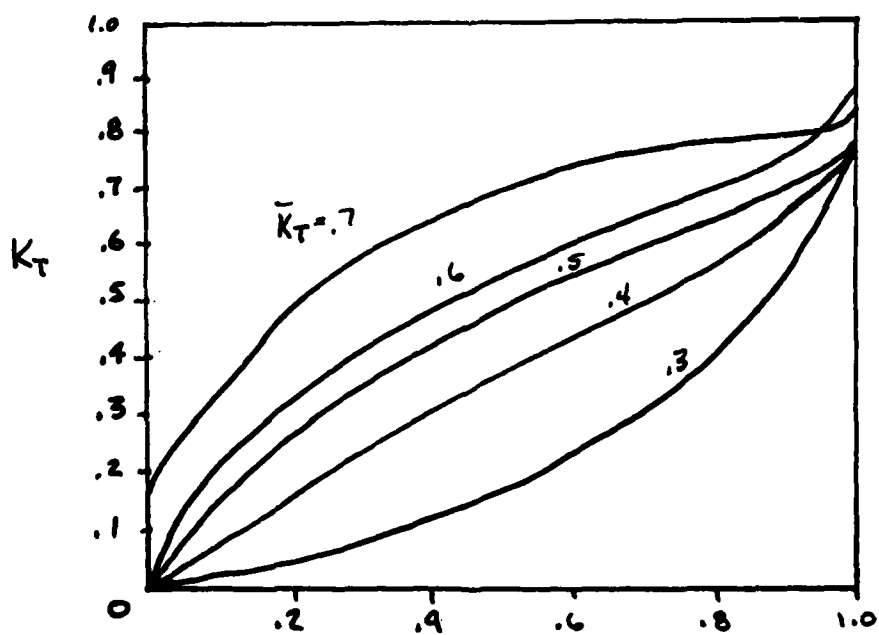


Fig 9. - Generalized monthly K_T curves

Using the generalized curves it is possible to approximate the performance of the collector.

To find the utilizability, the shaded area under the curve in Fig 10 must be found. The curve is divided horizontally into any number of segments. Fig 10, as an example, uses 10 intervals. Shift these intervals to the left so that half of the first interval is cut off, i.e., the first interval goes from $f = 0$ to $f = .05$. Each successive interval is .1 wide, except for the 11th interval which goes from $f = .95$ to $f = 1$. Using the value of f at the midpoint of each interval excluding intervals 1 and 11, enter Table 1 and find the value for K_T for the given long term clearness index. Interpolation will be necessary unless the \bar{K}_T happens to be one of the values of f . This value of K_T is then used in equations (27) through (30). This results in a value of $\frac{I_{Tt}}{\bar{I}_{Tt}}$. By subtracting the value of $\frac{I_c}{\bar{I}_{Tt}}$ from the value of $\frac{I_{Tt}}{\bar{I}_{Tt}}$ and multiplying it by the width of the section (in this example .1) the area under the curve and above the $\frac{I_c}{\bar{I}_{Tt}}$ value for each section from $f = .05$ to $f = .95$ is found. For section 1 and section 11 the width of the section is .05 instead of .1. If any section is negative it means energy

would be lost from the collector so that value of

$\frac{I_{Tt}}{I_{Tt}} - \frac{I_c}{I_{Tt}}$ is set equal to zero. Adding all the sections

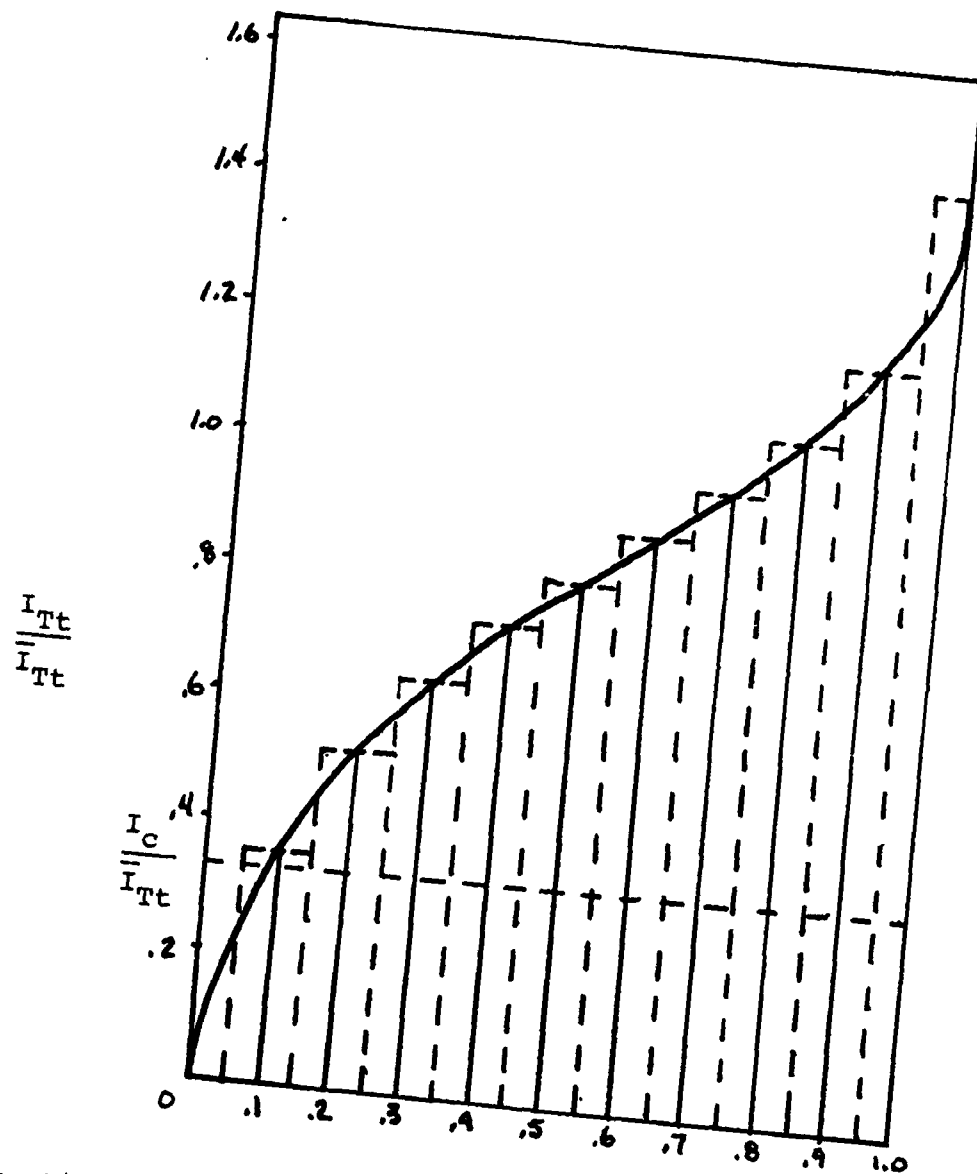
together gives the value of the utilizability.

In some systems it may be desirable to use one fluid for collection and another for storage and a heat exchanger to transfer the heat. There are several reasons for this:

1. Water might freeze in the collector on cold nights and damage the collector.
2. Water might corrode the collector if more expensive corrosive-proof materials are not used.

If this system is used there is a loss of efficiency in the heat exchanger because the collector fluid temperature is raised.

F. de Winter (Ref 3) found a factor that makes it possible to find the amount of heat transferred when using a separate fluid in the collector and using a heat exchanger to transfer the heat to the storage fluid. In using this factor, the temperature difference used to find I_c no longer is the difference between the collector fluid going into the collector and the ambient temperature. It is now the difference between the temperature of the storage fluid as it enters the heat exchanger and the ambient temperature.



Fractional time, f , during which daily total radiation $\leq H$

Fig 10. Sample Radiation Distribution Curve
Division for Integration

The heat exchanger factor is given by the equation:

$$FR' = \frac{FR}{1 + \left(\frac{FRU}{GC_p}\right) \left(\frac{1}{EFF} - 1\right)} \quad (31)$$

where G is the mass flow rate of the collector fluid divided by the area of the collector, C_p is the specific heat at constant pressure of the collector fluid, and EFF is the efficiency of the heat exchanger.

This equation can be used for a system that just uses water as a collector fluid and storage fluid with no heat exchanger by designating the efficiency of the heat exchanger as 1. When this is done, the equation becomes $FR' = FR$.

The amount of heat transferred to storage then becomes:

$$Q = AC \times F'_R + \bar{I}_{Tt} \times UT \times (\tau\alpha) \quad (32)$$

B. Energy Transfer and Storage

Using the amount of energy being transferred to storage, the amount of energy being taken from the system and the characteristics of the storage tank, it is possible to determine the temperature of the storage fluid, the amount of backup energy required and the total energy required.

If a system similar to system 1 is used (Fig 1), the equation to find the new storage fluid temperature each hour is (Ref 4):

$$T_{\text{new}} = T_{\text{old}} + (Q - UA (T_{\text{old}} - T_{\text{ROOM}})) / \text{MASS} \quad (33)$$

where T_{ROOM} is the temperature of the air in the room that encloses the storage tank, MASS is the amount of water in storage, and UA is the heat loss coefficient-area product given by the equation:

$$UA = k \times \text{AREA} / \text{thc} \quad (34)$$

where K is the conductivity of the insulation material, AREA is the surface area of the storage tank and thc is the thickness of the insulation. With this system there is no auxiliary, or backup, energy source, so the operator must wait each day until enough solar energy has been utilized to raise the temperature of the water to the desired level. Consequently, no load has been included and this equation will only give the temperature of the water each hour.

If the collector and storage system are similar to system 2 (Fig 2), then the following equation is used to find the temperature each hour (Ref 4):

$$T_{\text{new}} = T_{\text{old}} + (Q - L - UA (T_{\text{old}} - T_{\text{ROOM}})) / \text{MASS} \quad (35)$$

where L is the load in BTU removed from the storage tank to the conventional water heater and is found by the equation:

$$L = HL \times \text{CPS} (T_{\text{new}} - T_{\text{in}}) \times 8.336 \quad (36)$$

where HL is the hourly load, in gallons, on the water heater, T_{in} is the temperature of the water as it enters the system from the water main and 8.336 is the conversion factor to convert from gallons to pounds.

The conventional water heater draws its water from the storage tank. If the temperature of the water in the storage tank is below the specified temperature of the water. The amount of energy required is found by the equation:

$$Q_{\text{aux}} = HL \times \text{CPS} (T_5 - T_{\text{new}}) \times 8.336 \quad (37)$$

where T_5 is the specified temperature for the hot water.

If the system in use is similar to system 3 (Fig 3), then the equation to use is:

$$T_{\text{new}} = T_{\text{old}} + \frac{(Q - L - UA (T_{\text{old}} - T_{\text{ROOM}}))}{\text{MASS} \times \text{CPS}} \quad (38)$$

The backup energy used is the same as used in system 2.

Summing values for Q , Q_{aux} and L for all hours of the day and then multiplying by the number of days in the month results in the monthly solar energy usage, backup energy usage and load. The percentage of energy usage supplied by solar is then simply the solar usage divided by the total energy usage.

III Cost Analysis

A cost analysis must be done over a long term to provide any kind of accuracy. The program takes each monthly value and adds it to previous monthly values to give a year-to-date figure.

To be cost effective a solar energy system must have more in fuel costs than the cost of buying and maintaining the system.

Numerous items must be considered. These include the cost of fuel, inflation, property taxes, income taxes, insurance and maintenance, as well as the initial cost of the solar system equipment. A life cycle cost analysis method similar to that used by Beckman, Klein and Duffie (Ref 2) is used in this program. This method makes it possible to compare future costs with today's costs by reducing all costs to present worth. In other words, how much would have to be invested today in order to have a certain amount available at some future date to meet anticipated costs. The cost for heating is calculated for each year of the life of the system, and then these costs are discounted to the present value and then summed to find the life cycle cost. After figuring all future costs and discounting them to present value, it is possible to see if any money will be saved by installing a solar energy system.

Life cycle cost analysis is considered by many economists as the surest approach in economic decision making (Ref 10). However, it does have one major drawback. The costs and interest rates must be predicted into the future. If the future costs assumptions are made too pessimistically, the system may not be cost effective, and if the assumptions are too optimistic the predicted life cycle savings may be far greater than will actually be realized. It is left up to the operator to determine if the assumptions are right.

The yearly cost of a solar energy system or any other energy system include the annual payment for principal and interest to buy the equipment, fuel costs, maintenance and insurance costs and property tax. This may be reduced by a tax savings. By finding the life cycle costs for both the solar energy system and a conventional system, a comparison can be made to find if the solar system is cost effective. This type of analysis is called a savings analysis and is useful because it is not necessary to evaluate costs that are common to both systems, for example, much of the duct work would probably be the same with either system. In using this savings method a negative value for savings is possible, which means the system costs more than it saves and you would lose money.

Solar savings for a residence is the sum of the fuel savings and the tax savings minus the sum of extra payments for the equipment, extra insurance and maintenance and extra property taxes. The tax savings is the sum of extra interest paid plus extra property tax paid all multiplied by the tax rate.

It is assumed that over the term of analysis the costs are inflating at a fixed percentage per year. Individual yearly inflation and discount rates throughout the term may fluctuate, but over the entire term, average values are used. The discount rate is the best alternative investment for the prospective solar energy system owner, for example, long-term certificates of deposit or bonds. To calculate the costs based on inflation, an inflation-discount function is used. This function is given by the equation (Ref 2):

$$DI = \frac{1}{d - i} \left[1 - \left(\frac{1 + i}{1 + d} \right)^N \right], \text{ if } i \neq d \quad (39)$$

$$DI = N/(1 + i), \text{ if } i = d \quad (40)$$

where i is the yearly inflation rate, d is the yearly discount rate and N is the number of years the life cycle cost analysis is to run.

The following figures must be input into the program by the operator:

1. The annual mortgage interest rate that would be paid on a loan secured to purchase the solar equipment.
2. The number of years you would be making payments on the loan.
3. The downpayment as a fraction of the initial investment, e.g., 10 percent down.
4. Costs of equipment that are dependent on the area of the collector. These costs include the cost of the collector, labor for installation, possible credits for savings on the roof, expenses for roof support modifications, part of the storage unit and all other costs that increase in proportion to the collector area. This cost is entered as a cost per unit of collector area.
5. Costs of equipment that are independent of the collector area. These costs include the cost of pumps, fans, controls, extra ductwork, heat exchangers, the rest of the storage unit and all other costs that do not increase in proportion to the collector area. This term is just measured in dollars.

There are two separate costs listed for fuel for heaters, a backup heater and a conventional heater. For a water heating system the backup heater and the conventional heater are probably the same unit. However, for space

heating, they could be different. For instance, the backup furnace might be a woodburning stove and a conventional gas furnace could be installed in the home already, so the comparison would be between what the costs are for the solar/wood burning stove and the costs for gas for the conventional furnace.

6. Present cost of fuel used by the solar system backup heater. This is the cost of fuel for the first year and is entered as cost per amount of energy, e.g., dollars per million BTU. The heating values of different fuels are (Ref 2):

Natural gas	1100 BTU/cu. ft.
Fuel oil	140000 BTU/gal
Electricity	3400 BTU/kW-hr.

7. Present cost of fuel for the conventional system heater. This is entered in the same manner as entry 6.

8. Efficiency of solar backup.

9. Efficiency of conventional heater.

10. The property tax rate as a fraction of the initial investment. If the assessed valuation of the residence is increased when a solar energy system is added, then more taxes will be paid. This entry is used to calculate the dollars paid in taxes on each dollar invested.

11. Effective income tax bracket. Most of the tax savings are in the form of income tax deductions. The

effective income tax bracket is a combination of state and federal tax brackets: the sum of the two minus the product of the two, assuming the same deductions are allowed for state and federal taxes.. The sum of the two is reduced by the product of the two when the state taxes are deducted from federal taxes.

12. Extra insurance and maintenance costs as a fraction of the initial cost. The extra insurance is the premium increase because of the increase in value of the house. The maintenance cost is the total amount of maintenance anticipated over the life cycle divided by the life cycle.

13. General inflation rate per year. This is the average yearly inflation rate for the life cycle.

14. Fuel inflation rate. This is the average yearly inflation rate of the cost of fuel.

15. Discount rate. This is the after tax return on the best alternative investment.

16. Term of economic analysis. This is the number of years the analysis is to cover. It can be the term of the mortgage, the expected life of the system, or any other time frame.

17. First year non-solar fuel expense. This is the cost of conventional fuel for the first year that would be paid if a solar system was not installed.

Now the inflation-discount function is used to determine

costs in present value. AA is the function value with an inflation rate equal to the fuel inflation rate, a discount rate equal to the discount rate and figured over the term of economic analysis. BB is the like AA except that the inflation rate is equal to the general inflation rate. CC is the function with an inflation rate equal to the annual mortgage interest rate, a discount rate equal to the discount rate and figured over the term of the mortgage or the term of the economic analysis, whichever is shorter. EE is the function with an inflation rate of zero, a discount rate equal to the annual mortgage interest rate and figured over the term of the mortgage. FF is the function with an inflation rate of zero, a discount rate equal to the discount rate and figured over the term of the mortgage or the term of economic analysis, whichever is shorter.

AA and BB represent the sum of present value of all yearly payments of expenses that are inflating. CC, EE and FF are used for loan calculations.

To find the present value of the payments (GG) on a loan of one dollar borrowed for the term of mortgage with an interest rate equal to the annual interest rate and a discount rate equal to the discount rate, divide FF by EE.

To find the present value of all interest paid (HH) on the one dollar loan use the following equation:

$$HH = GG + CC \left(AMIR - \frac{1}{EE} \right) \quad (41)$$

where AMIR is the annual mortgage interest rate.

To find the life cycle capital cost (II) as a fraction of the initial investment use the equation:

$$II = DNPMT + (1 - DNPMT) (GG - HH \times TAXBRKT) \quad (42)$$

where DNPMT is the down payment as a fraction of the initial cost, and TAXBRKT is the effective income tax bracket.

To find the insurance and maintenance costs (JJ) as a fraction of the initial investment, use the following equation:

$$JJ = BB (EXTINS) \quad (43)$$

where EXTINS is the extra insurance and maintenance costs as a fraction of the initial investment.

To find the property tax (KK) as a fraction of the initial investment use the following equation:

$$KK = (TAXRT) BB (1 - TAXBRKT) \quad (44)$$

where TAXRT is the property tax rate as a fraction of the initial cost.

To find the total life cycle cost as a fraction of the initial investment use the equation:

$$OO = II + JJ + KK \quad (45)$$

It is now possible to perform the calculations to find the life cycle savings of the solar energy system. The total investment in solar (R3) is found by using the following equation:

$$R3 = AC \times AREACST + ARINCST \quad (46)$$

where AREACST is the cost of equipment that is dependent on the collector area, and ARINCST is the cost of equipment that is independent of the collector area.

The first year fuel expense (R4) is the cost of fuel with a solar energy system in use. It is found using the equation:

$$R4 = TLOAD (1 - R2) BUFCOST/BUEFF \quad (47)$$

where TLOAD is the yearly load in BTU, R2 is the percentage of the energy supplied by the solar system, BUFCOST is the cost of fuel for the backup heater and BUEFF is the efficiency of the backup heater.

The fuel savings is found by subtracting R4 from the first year non-solar fuel expense to find the first year value and then multiplying it by AA to get the life cycle savings.

The expenses for the residence are found by taking R3 and multiplying by 00 to get the life cycle costs. The life cycle savings are the difference between the fuel savings and residential expenses.

IV System Simulation

The program was used to simulate a residence in Columbus, Ohio. The day ambient temperature, radiation, temperature in the room, and the number of days in the month are given in Table 2. The other values that were used are:

1. Latitude - 40 degrees
2. Dirt Factor - .02
3. Percent of time more than one inch of snow present
- 0.
4. Number of covers - 2
5. Slope of the collector - 55 degrees
6. Azimuth angle - 0 degrees
7. Area of collector - 50 sq. ft.
8. Thickness of cover material - .23 cm.
9. Extinction coefficient of cover material - .161/cm.
10. Index of refraction of cover material - 1.526
11. Absorbitivity of the absorber plate - .95
12. Heat removal efficiency - .9
13. Heat loss coefficient - .7
14. Flow rate of collector fluid - 550 lb/hr (based on
a flow rate of .022 gal/min/sq. ft.
15. Specific heat of collector fluid - 1
16. Initial temperature of fluid in storage - 70.2
degrees F.

17. Temperature of water from main - 55 degrees F
18. Efficiency of heat exchanger - 1
19. System in use - 2
20. Amount of water in storage - 80 gallons (based on
1.6 gallons of storage per square foot of collector)
21. Surface area of the storage tank - 28.1 sq. ft.
(based on a tank that is two and one-half times as
tall as it is in diameter)
22. Thickness of insulation around storage tank - 3. in.
23. Conductivity of insulating material - $\frac{.25 \text{ BTU} \cdot \text{in.}}{\text{hr} \cdot \text{sq.ft.}} \cdot ^\circ\text{F}$
24. Specific heat of storage fluid - 1
25. Number of days to run - 1
26. Daily hot water usage - 100 gallons
27. Annual mortgage interest rate - 15 percent
28. Term of mortgage - varied (20 years, 10 years,
5 years)
29. Down payment - 10 percent
30. Fuel cost for backup heater - \$3.26/million BTU
31. Fuel cost for conventional heater - \$3.26/million BTU
32. Efficiency of backup heater - .55
33. Efficiency of conventional heater - .55
34. Property tax rate - 0.0
35. Tax bracket - .40
36. Extra insurance and maintenance costs - .01
37. General inflation rate - 8 percent

- 38. Fuel inflation rate - 12 percent
- 39. Discount rate - varied (6 percent, 8 percent)
- 40. Term of analysis - 20 years
- 41. Area dependent cost - \$20/sq. ft.
- 42. Area independent cost - \$1000

Table 2. Average Monthly Data for Columbus, Ohio

<u>Month</u>	<u>Day</u>	<u>Ambient Temp °F</u>	<u>Average Daily Radiation on a Horizontal Surface</u>	<u>Room Temp °F</u>	<u>Number of Days in Month</u>
Jan	17	27.2	472	68	31
Feb	47	29.8	737	68	28
Mar	75	39.5	1095	68	31
Apr	105	51.7	1442	70	30
May	135	61.0	1737	75	31
Jun	162	70.8	2072	80	30
Jul	198	74.5	1998	80	31
Aug	228	72.8	1759	80	31
Sep	258	66.3	1556	75	30
Oct	288	55.3	1054	70	31
Nov	318	41.8	649	68	30
Dec	344	33.2	476	68	31

In this simulation the collector size, the term of the mortgage and the discount rate were varied while the other parameters were held constant. The fuel cost is the cost for natural gas, which is approximately one-third the cost of electricity, so if any other fuel were used, the savings would be greater.

When the term of the mortgage was increased, the savings were shown to decrease (Table 3). This is understandable because when a given amount is borrowed, the longer the term of the loan the more interest is paid.

The discount rate had two effects on the savings. First, when it was increased from 6 percent to 8 percent the amount of savings was reduced by over 50 percent. Second, when the discount rate was increased the most cost-effective size of the collector was reduced. This just shows that if the discount rate is high enough, it will be more economically feasible to invest the money elsewhere instead of purchasing solar equipment.

Varying the size of the collector showed how to find the most cost-effective area. With the collector too large the temperature in the storage tank gets too high and the conventional water heater will vent the excess pressure. This is then energy that is wasted. When the water in the storage tank gets hotter, more heat is lost to the room because of the larger temperature difference. As shown in

Table 4, the percent of the solar energy that is collected which is then lost to the room increases with increasing collector size. The data in Table 4 also takes into account the amount of temperature gain from January 1 to December 31. With all collector sizes, the temperature in the late afternoon was highest during the months from July through October (Table 4). The temperatures given are for average days for each month, so for days that are above average in the amount of energy collected will have even higher temperatures. So it is easy to see that with collectors of 85 or 100 square feet the temperature in storage will be too high and energy will be lost. With a storage tank that is inside the residence the heat that is lost to the air simply adds to the air conditioning load during the hotter months, and reduces the heating load in the colder months. If this facet is disregarded, then the most cost-effective size of collector can be found from Table 3. Considering the higher temperatures with the larger collector areas, my choice would be a 75 square foot collector.

Table 3. Savings

Collector area	50	65	75	85	100
Mortgage term	5	5	5	5	5
Discount rate .06 .08	\$517.77 \$212.12	\$672.03 \$300.11	\$741.02 \$331.71	\$916.58 \$464.72	\$816.46 \$333.19
Mortgage term	10	10	10	10	10
Discount rate .06 .08	\$442.21 \$189.61	\$583.06 \$273.51	\$643.41 \$302.63	\$816.49 \$434.89	\$696.82 \$297.54
Mortgage term	20	20	20	20	20
Discount rate .06 .08	\$310.47 \$153.89	\$428.27 \$231.53	\$473.25 \$256.48	\$641.20 \$387.55	\$488.23 \$240.98

Table 4. Solar Data

Collector Area (sq. ft.)	50	65	75	85	100
Maximum Temp. (F)					
Jul	115.6	122.6	126.7	130.0	135.3
Aug	118.8	126.1	130.5	134.4	139.7
Sep	125.8	133.7	138.4	142.5	148.2
Oct	118.2	126.5	130.8	136.0	141.8
Total solar energy collected (BTU)	10963390.7	13515390.5	15099903.9	16618827.7	18782598.9
Total solar energy collected accounting for tank loss (BTU)	10497705.0	12654798.4	13923681.5	15068184.9	16604486.4
Tank loss as percent of energy collected	3.7	4.4	4.8	5.4	6.1
Percent of energy supplied by solar	40.6	48.9	53.8	58.3	64.2

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Appendix A

Program Instructions

This program is a simulation of a solar energy system for use on a small scale, such as in a residence. It is designed to allow the operator to change any of a number of variables to find what effect the variable has on the useful energy collected. It also allows the operator to perform a cost analysis of the solar energy system.

As in other solar-energy design simulations, the long term average performance, instead of instantaneous rates of energy collection and utilization, is used because of the variability in the latter due to the weather. Consequently, monthly average daily data is used to calculate the performance. This data is applied to an "average" day during the month and multiplied by the number of days in the month to arrive at monthly totals. The day used for the "average" day for each month is the day that most closely matches the average day data for the month. This day is not necessarily the midday of the month, see Table A-1. (Ref 7)

Table A-1 - Recommended Average Day for Each Month

<u>Month</u>	<u>Date</u>	<u>Day of the year</u>
January	17	17
February	16	47
March	16	75
April	15	105
May	15	135
June	11	162
July	17	198
August	16	228
September	15	258
October	15	288
November	14	318
December	10	344

To use this program one must input data about the weather, position and orientation of the collector and the Earth, characteristics of the collector and the energy transfer and storage system, and the costs involved.

Much solar insolation data has been and is being collected and tabulated by the U.S. Weather Bureau at approximately 80 cities across the country. Other data is recorded and tabulated by the U.S. Weather Bureau at all their stations.

Data about the characteristics of the collector and the energy storage and transfer systems can be obtained from

manufacturers or found in engineering handbooks such as the "ASHRAE Handbook of Fundamentals".

Data that can be obtained from the U.S. Weather Bureau for each month:

1. The average daytime ambient temperature.
2. Monthly average daily total radiation on a horizontal surface.
3. Percentage of the time that snow of greater than one inch thickness is present.

Data that is a function of the collector position and orientation:

1. Slope of the collector from horizontal.
2. Azimuth angle, i.e., the angle between the collector surface normal and the local meridian.
3. Latitude of the collector.

Data on the characteristics of the collector:

1. Number of covers on the collector.
2. Surface area of the collector.
3. Thickness of the cover material.
4. Heat removal efficiency.
5. Heat loss coefficient.
6. Extinction coefficient of the cover material.
7. Index of refraction of the cover material.
8. Absorptivity of the collector absorber plate coating.

9. Specific heat at constant pressure of the collector fluid.

10. Specific heat at constant pressure of the storage fluid.

11. Conductivity of the insulation around the storage tank.

Other data includes:

1. Dirt factor, this is .02 unless it is known from previous tests to be some other value.

2. Flow rate of collector fluid through the collector.

3. Initial temperature of fluid entering the collector.

4. Temperature of room enclosing the storage tank.

5. Temperature of water as it enters the storage tank from the main.

6. Effectiveness of the heat exchanger.

7. Amount of fluid in the storage tank.

8. Surface area of the storage tank.

9. Thickness of the insulation around the storage tank.

10. Number of consecutive days in a month the program is to run.

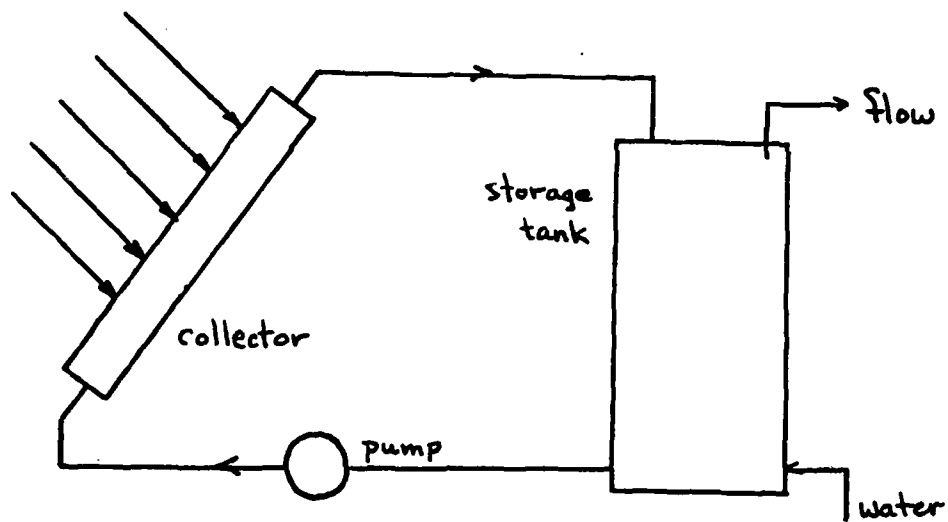


Fig A-1 System 1

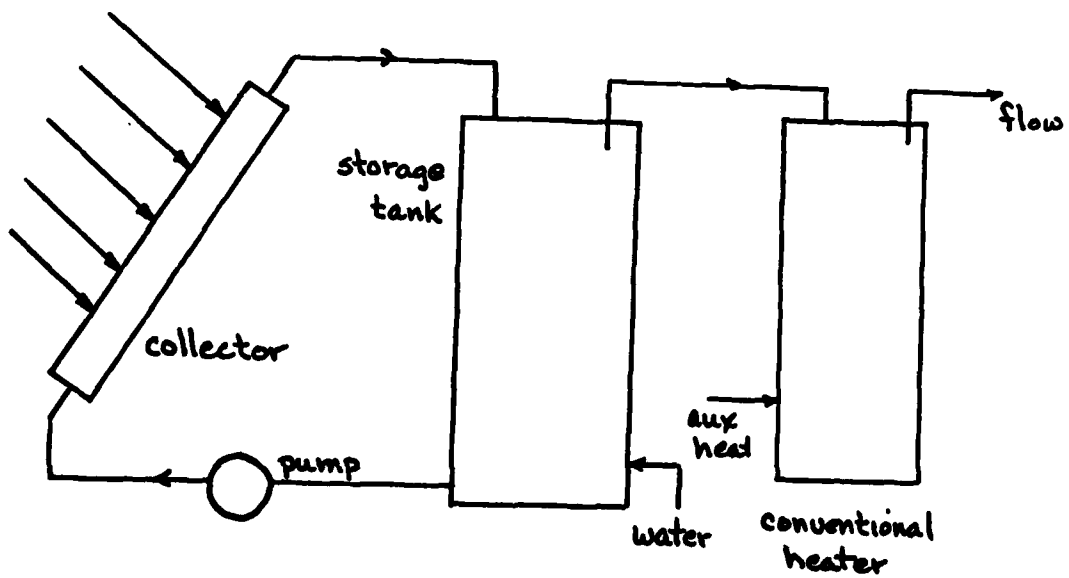


Fig A-2 System 2

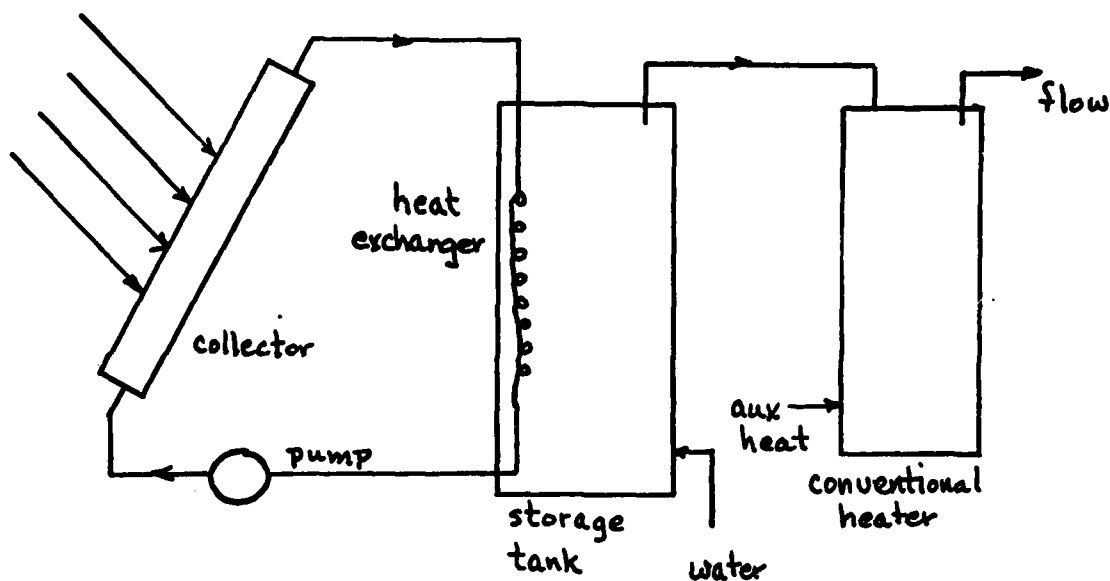


Fig A-3. System 3

Unless a system like the system in Fig A-1 is used, the load used must be determined before the program is started and entered on DATA Cards. The total load is found by assuming that on the average, a family will use 25 gallons of hot water per person per day. The DATA cards are broken into 24 hourly amounts. The figure to enter for each hour is the percentage of the daily total that is used that hour, (e.g., DATA LOAD/.01, 0.0, 0.0, 0.0, 0.0, 0.0, .05, .10, .10, .05, .07, .12, .../)

The operator must decide how many intervals to use on the generalized K_T curve to integrate the area under the curve to find the utilizability. The values of f at the

midpoint of each interval is used and must be entered on a DATA card. The values of f to enter on the DATA cards are found by dividing one by the number of intervals. There will be one more value of f than there are intervals. The first value of f will always be 0. and the last value will always be 1. For example, if ten intervals are desired then the values of f will be:

DATA F/0., .1, .2, .3, .4, .5, .6, .7, .8, .9, 1.0/.

To integrate the area under the generalized K_T curve the values of K_T for each value of f on the DATA card must be entered on the input data cards (cards 35a-1). The values of K_T are found on Table A-2. Find the column that matches the value of \bar{K}_T for the month (interpolation between columns may be necessary). Proceed down the column to the first value of f (interpolation is probably necessary) and read the value of K_T in the left column. This value will be entered on card 35a. Next, proceed down the \bar{K}_T column to the next value of f and read the value of K_T in the left column. Enter this value on card 35b. Do this for all values of f .

After deciding on the number of intervals, the DIMENSION card must be completed. All values on the DIMENSION card will be dimensioned as the number of intervals plus one, except for the flow, which will always be 24.

Table A-2. Generalized K_T Curve Values

Value of f

K_T	\bar{K}_T	.3	.4	.5	.6	.7
.04		.073	.015	.001	.000	.000
.08		.162	.070	.023	.008	.000
.12		.245	.129	.045	.021	.007
.16		.299	.190	.082	.039	.007
.20		.395	.249	.121	.053	.007
.24		.496	.298	.160	.076	.007
.28		.513	.346	.194	.101	.013
.32		.579	.379	.234	.126	.013
.36		.623	.438	.277	.152	.027
.40		.687	.493	.323	.191	.034
.44		.748	.545	.358	.235	.047
.48		.793	.601	.400	.269	.054
.52		.824	.654	.460	.310	.081
.56		.861	.719	.509	.360	.128
.60		.904	.760	.614	.410	.161
.64		.936	.827	.703	.467	.228
.68		.953	.888	.792	.538	.295
.72		.967	.931	.873	.648	.517
.76		.979	.967	.945	.758	.678
.80		.986	.981	.980	.884	.859
.84		.993	.997	.993	.945	.940
.88		.995	.999	1.000	.985	.980
.92		.998	.999		.996	1.000
.96		.998	1.000		.999	
1.00		1.000			1.000	

The output of the program includes all input data to facilitate trouble shooting. The output is broken down into hourly, monthly and yearly values. For each month the declination, which is the angle of the sun at solar noon with respect to the plane of the Earth's equator with angles north positive, is given. The sunset hour angle is the angle between the collector surface normal and the sun's rays at sunset. If this value is greater than 90 degrees, the sun actually sets behind the plane of the collector surface so the collector is not collecting any beam radiation after the sun passes through the plane. The extraterrestrial radiation on a horizontal surface is the amount of radiation that reaches the Earth's atmosphere at the given latitude. The long term clearness index is the fraction of the radiation that actually reaches the collector. It is never 1 because the radiation is reflected and absorbed by clouds, pollution and any other particles that are suspended in the atmosphere.

The hourly output begins with the hour from midnight to one. Only items that are figured each hour are listed as output. During every hour the storage tank can exchange heat with the surroundings to the temperature of the fluid in storage is listed. The load on the system can be used during all hours and the backup heater must be used to furnish the required energy, so the backup energy used is listed.

If the sun is not high enough or is not in front of the collector then no energy is collected and only the solar zenith angle, which is the angle between the sun's rays and the local vertical, the angle between the sun's rays and the collector surface normal, and the ground reflectance are added to the number of items listed.

When the sun is in a position to allow the collector to operate, the monthly average instantaneous total radiation on a tilted surface is listed. This is the hourly amount of radiation that is incident on each square foot of collector area. The total transmittance is the fraction of the radiation that is not absorbed or reflected by the cover system. The shading factor is the fraction of the collector absorber plate that is shaded by the vertical sides of the collector. The effective transmittance-absorptance product is the fraction of the total radiation incident on the cover that is absorbed by the absorber plate.

The ratio of critical radiation to monthly average instant total radiation on a tilted surface is the ratio of the critical radiation to the monthly average hourly radiation on the surface. The critical radiation is the irradiation at which energy is collected by and lost from the collector at the same rate. The utilizability is the fraction of the energy that is actually utilized and is

used to find the amount of energy that is transferred to storage.

At the end of the day the hourly totals are added to give daily totals and then are multiplied by the days in the month to give monthly totals. These monthly totals include:

1. Total useful solar energy for the month (BTU).
2. Monthly amount of hot water used (gal).
3. Monthly backup heat used (BTU).
4. Monthly total load used (BTU).

These monthly totals are added at the end of each month to give year-to-date values of useful solar energy, backup heat used, and total energy used.

To determine if the solar energy system is cost effective, numerous items must be considered. These include the cost of fuel, inflation, property taxes, income taxes, insurance, maintenance as well as the initial cost of the solar system equipment.

A life cycle cost analysis method similar to that used by Beckman, Klein and Duffie (Ref 2) is used in this program. In this system the net cost for heating is calculated for each year and then discounted to present year dollars, which accounts for the time value of money. This can be done for each of the systems (solar and conventional) to determine the most cost effective.

In figuring the values to enter on the data cards, many items must be considered and several rates must be predicted for the term of the analysis as average yearly rates, e.g., average yearly inflation rate.

If the backup system heater and conventional heater are the same then the entries for cost of fuel and efficiencies are the same, i.e., do not skip any input card. For an electric heater the efficiency is 100%, for oil or gas the efficiency can be as low as 50% or 60%. (Ref 2)

The property tax rate is used to calculate the dollars paid in taxes on each dollar invested. The largest tax savings is in the income tax reductions. The tax bracket can be figured as the state plus federal tax bracket minus the product of the two, assuming the same deductions are allowed for both.

The first year non-solar fuel expense is the total expense for fuel without a solar energy system. It is found by the annual heating load multiplied by the fuel cost divided by the heater efficiency.

The outputs labeled LOAN PAYMENT, LOAN INTEREST, CAPITAL COST, INSURANCE AND MAINTENANCE COST, and PROPERTY TAX are life cycle values as a fraction of the initial investment. The output labeled RESIDENTIAL COSTS represents the total life cycle cost as a fraction of the investment.

The output labeled INVESTMENT IN SOLAR is the sum of collector area dependent and independent costs. The FIRST YEAR FUEL EXPENSE is the total heating load multiplied by the fraction of energy not supplied by solar multiplied by the cost of the solar backup fuel divided by the heater efficiency. The output labeled FUEL SAVINGS is the life cycle fuel savings. It is the difference between the fuel expense with solar and without solar times the inflation-discount factor used to find the life cycle value. The output labeled RESIDENTIAL EXPENSES is the life cycle expense and the output labeled RESIDENTIAL SAVINGS is the life cycle saving for the solar energy system.

Appendix B

Data Cards

This appendix contains a list of all the cards in the input data deck. All cards must be input in the following order. Do not skip any card. All input data is real except where noted.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
1	LATD	XX.X	Degrees and tenths of a	The latitude of the collector.
2	SD	XX.X	Degrees	Slope of the collector measured from horizontal.
3	CN	X.	none	Number of covers on the collector.
4	DGAMMA	XX.X	Degrees	The azimuth angle of collector (i.e., the angle between the collector surface normal and the local meridian). Angles west of the local meridian are positive.
5	AC	XXX.X	Sq. Ft.	The surface area of the collector.
6	THC	.XXX	Inches	The thickness of one layer of cover material.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
7	EC	.XXX	per Inch	Extinction coefficient of the cover material. The units on this and on the thickness must be coordinated so that when multiplied, the product is dimensionless.
8	ETAC	X.XXX	none	Index of refraction of the cover material.
9	ALPHAN	.XXX	none	Absorptivity of the collector absorber plate coating.
10	FR	.XX	none	Heat removal efficiency of the collector.
11	U	.XX	none	Heat loss coefficient of the collector.
12	FLOWC	XXXX.X	lb _m /hr	Mass flow rate of collector fluid.
13	CPC	X.XX	none	Specific heat at constant pressure of the collector fluid.
14	DF	.XX	none	Dirt factor.
15	T3	XXX.X	Degrees F	Initial temperature of the fluid in the storage tank.
16	TIN	XX.X	Degrees F	Temperature of water as it enters the storage tank from the main supply

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
17	EFF	X.XX	none	Efficiency of heat exchanger. If no heat exchanger is being used between the collector fluid and the storage fluid, then enter 1.
18	PROG	X.	none	Type of energy transfer and storage system in use. See Appendix A for description of systems. Enter 1 if the system is similar to that in Fig A-1. Enter 2 if the system is similar to that in Fig A-2, Enter 3 if the system is similar to that in Fig A-3.
19	MASS	XXX.	Gallons	Amount of water in the storage tank.
20	AREAST	XXXX.X	Sq. Ft.	Surface area of the storage tank. Units on this item and the next two must be coordinated.
21	THICKST	X.X	Inches	Thickness of insulation around storage tank.
22	CONDST	.XX	$\frac{\text{BTU} - \text{in.}}{\text{hr-sq. ft.}-^{\circ}\text{F}}$	Conductivity of insulating material around storage tank.
23	CPS	X.XX	none	Specific heat at constant pressure of the storage fluid.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
24	DAYFLOW	XXX.X	Gallons	Daily amount of hot water usage. An average figure is 20 or 25 gallons per person per day.
25	INT	XX	none	Number of intervals desired on the generalized K _T curve (INTEGER).
26	ND	X	none	Number of consecutive days the simulation is to run. (INTEGER)
27	MON	XX	none	This is the number of months you want the program to run. (INTEGER).

Cards 28 through 351 must be entered for each month the program is going to run.

28	DAY	XXX.	none	The day of the year (January 1 is day 1., December 31 is day 365).
29	TAMB	XX.X	Degrees F	The average ambient temperature for the month.
30	HAVG	XXXX.X	BTU/hr-sq.ft.	Long term average daily radiation on a horizontal surface.
31	KTAVG	.XXX	none	Long term clearness index. If it is not known, enter 0.0 and the program will compute it.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
32	CP	XXX.X	none	The percent of time the ground is covered with at least one inch of snow (40 percent is entered as 40., not .4).
33	TROOM	XX.X	Degrees F	Temperature of room enclosing the storage tank.
34	DAYMON	XX.	none	Number of days in the month being considered.
35a-1	DKT(L)	.XXX	none	Values of K_T for the number of intervals plus one taken from the K_T curve chart. See Appendix A for instructions on finding values for K_T .

Cards 36 through 51 are for the cost analysis portion. If a cost analysis is not desired, do not enter any more data cards and the program will stop automatically.

36	AMIR	.XXX	none	Annual mortgage interest rate one would pay for a home improvement loan to purchase solar equipment. (10 percent is entered as .1)
37	YRMORT	XX.	Years	Term of mortgage. The number of years to pay back the loan.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
38	DNPMT	.XX	none	Down payment as a fraction of the initial cost. (10 percent down is entered as .1)
39	BUFCOST	XX.XX	<u>Dollars</u> million BTU	Cost of fuel for backup heater.
40	CONFCST	XX.XX	<u>Dollars</u> million BTU	Cost of fuel for conventional heater.
41	BUEFF	X.XX		Efficiency of the backup heater (75 percent efficiency is entered as .75)
42	CONEFF	X.XX		Efficiency of the conventional heater.
43	TAXRT	.XXXX		Property tax rate, as a fraction of the initial cost.
44	TAXBRKT	.XXX		Effective income tax bracket (federal + state - federal x state), if state and federal allow same deductions).
45	XTRINS	.XXX		Extra insurance and maintenance costs, as a fraction of the initial cost. These are the estimated lifetime costs divided by the lifetime and then entered as a fraction of the initial cost.

<u>Card No.</u>	<u>Nomen.</u>	<u>Input Format</u>	<u>Units</u>	<u>Explanation</u>
46	GENINF	.XXX		General inflation rate per year (10 percent is entered as .1)
47	FLINF	X.XXX		Fuel inflation rate per year.
48	DISCRT	.XXX		Discount rate, i.e., the after tax return on the best alternative investment.
49	ANALTRM	XX.	Years	Term of economic analysis, this can be the term of the mortgage, the anticipated life of the system, or any other term desired.
50	AREACST	XXXX.X	<u>Dollars</u> <u>sq. ft.</u>	Cost per unit of area for items that are dependent on the collector area, e.g. the collector, supports, installation charges and part of the storage unit.
51	ARINCST	XXXX.X	Dollars	Cost of the rest of the equipment that is not dependent on the collector area, e.g. pumps.

Appendix C

Computer Program

```

PROGRAM SOLAR1(INPUT,OUTPUT,TAPE 5=INPUT,TAPE6=OUTPUT)
REAL H,HAvg,H0,ITIT,ITT,KT,KTAVG,LAT,LATD,LOAD,MASS
REAL II,JJ,KK,LL,MFLCH,INFL,INSIX
DIMENSION UT(11),AVG(11),DKT(11),F(11),FLOW(24)
DATA F/0.9,.1,.2,.3,.4,.5,.6,.7,.8,.9,1.0/
DATA FLOW/.01,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.05,.07,.09,.07,.05,.04,.05,.02,
C.02,.02,.04,.07,.11,.1,.07,.06,.15/
READ*,LATD
WRITE(6,1125)LATD
READ*,SD
WRITE(6,1160)SD
READ*,CN
WRITE(6,1165)CN
READ*,DGAMMA
WRITE(6,1170)DGAMMA
READ*,AC
WRITE(6,1175)AC
READ*,THC
WRITE(6,1180)THC
READ*,EC
WRITE(6,1185)EC
READ*,ETAC
WRITE(6,1190)ETAC
READ*,ALPHAN
WRITE(6,1195)ALPHAN
READ*,FR
WRITE(6,1200)FR
READ*,U
WRITE(6,1205)U
READ*,FLOWC
WRITE(6,1210)
WRITE(6,1215)FLOWC
READ*,CPC
WRITE(6,1220)CPC
READ*,DF
WRITE(6,1145)DF

```

000100
000110

000130

000180
000190
000340
000350
000360
000370
000380
000390
000400
000410
000420
000430
000440
000450
000470
000490
000500
000510
000520
000530
000540
000550
000560
000570
000580
000590
000270
000280

```

READ*,T3
WRITE(6,1230)T3
READ*,TIN
WRITE(6,2155) TIN
READ*,EFF
WRITE(6,1240)EFF
READ*,PROG
WRITE(6,1245)PROG
READ*,MASS
WRITE(6,1250)MASS
MASS=MASS*8.336
READ*,AREAST
WRITE(6,1255)AREAST
READ*,THICKST
WRITE(6,1260)THICKST
READ*,CONDST
WRITE(6,1265)CONDST
READ*,CPS
WRITE(6,1270)CPS
READ*,DAYFLOW
WRITE(6,1300) DAYFLOW

READ*,INT
WRITE(6,1225)INT
READ*,ND
WRITE(6,1275)ND

C HOW MANY MONTHS DO YOU WANT THIS PROGRAM TO RUN?
READ*,MON
WRITE(6,1345) MON
YFLOW=0.
YBUQ=0.
YQTOT=0.
DO 3 J=1,MON
READ*,DAY
WRITE(6,1000)DAY
READ*,TAMB
WRITE(6,1130)TAMB

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000640

000680
000690
000700
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000730
000740

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000240
000250
000260
000290
000300
000310
000360
000570

READ*,HAVG
WRITE(6,1135)
WRITE(6,1140)HAVG
READ*,KTAVG
WRITE(6,1020)KTAVG
READ*,CP
WRITE(6,1150)
WRITE(6,1155)CP
READ*,TROOM
WRITE(6,1235)TROOM
READ*,DAYMON
WRITE(6,1290)DAYMON

C FIRST, DETERMINE THE AMOUNT OF RADIATION STRIKING THE COLLECTOR SURFACE.
C FIND THE DECLINATION(DELTA), THE SUNSET HOUR ANGLE (WS), THE
C EXTRATERRESTRIAL RADIATION ON A HORIZONTAL SURFACE (HO), THE LONG
C TERM CLEARNESS INDEX (KTAVG), AND THE MONTHLY AVERAGE DAILY DIFFUSE
C RADIATION ON A HORIZONTAL SURFACE (JAVG)

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000990

UAST=CONDS*AREAST/THICKST
PI=3.1415926536
RAD=57.2957795131
LAT=LATD/RAD
D=2.*PI*(284.+DAY)/365.
DELT=23.45*SIN(D)
DELTA=DELT/RAD
WRITE(6,1005)DELT
WS=ACOS(-TAN(LAT)*TAN(DELTA))
WSD=WS+RAD
WRITE(6,1015)WSD
OC=.633*(COS(2.*PI*DAY/365.))
OS=(COS(DELTA)*COS(LAT)*SIN(WS))+(WS*SIN(LAT)*SIN(DELTA))
HO=(24./PI)*432.*((1.+OC)*OS)
WRITE(6,1010)HO
IF(KTAVG.GT.0.) GO TO 4
KTAVG=HAVG/HO
WRITE(6,1020)KTAVG
IF(KTAVG.LE.0.35)GO TO 5

001100

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5      DAVG=HAVG*(.79-(.83*KTAVG))
10     GO TO 10
      DAVG=HAVG*(1.2-(2.*KTAVG))
      CONTINUE
      INTV=INT+1
      DO 6 L=1,INTV,1
      READ*,OKT(L)
      N=L-1
      WRITE(6,1280) N,OKT(L)
      CONTINUE
      WRITE(6,1025)
      WRITE(6,1030) DAVG
      S=SD/RAD
      GAMMA=DGAMMA/RAD
      DO 2 N=1,ND,1
      WD=-3.0107
      OSUM=0.0
      OBU=0.0
74 C   DO LOOP 1 IS COMPLETED FOR EACH HOUR OF THE DAY
      HR=12.
      HP=1.
      DO 1 I=1,24,1
      IF (HR.GT.12.) GO TO 86
      HR=HR
      GO TO 87
86     HR=HR-12.
87     IF (HP.GT.12.) GO TO 88
      HP=HP
      GO TO 89
88     HP=HP-12.
89     WRITE(6,1090) HR,HP
      HP=HP+1.
      HR=HR+1.
      C   FIND THE ANGLE BETWEEN THE COLLECTOR SURFACE NORMAL AND THE SUN'S RAYS
      C   (THETAT) AND THE SOLAR ZENITH ANGLE (THETAZ)
      IF (DGAMMA)7,8,9

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7  AS1=COS(LAT)/(SIN(GAMMA)*TAN(S))
   AS2=SIN(LAT)/TAN(GAMMA)
   ASR=AS1+AS2
   BS1=COS(LAT)/TAN(GAMMA)
   BS2=SIN(LAT)/(SIN(GAMMA)*TAN(S))
   BSR=TAN(DELTA)*(BS1-BS2)
   ABSQT=SQRT((ASR*ASR)-(BSR*BSR)+1.)
   WSM=ACOS(((ASR*BSR)+ABSQT)/(ASR*ASR+1.))
   WSO=ACOS(((ASR*BSR)-ABSQT)/(ASR*ASR+1.))
   WSR=-WSM
   WSS=WSO
   IF (WD.LT.WSR) GO TO 13
   IF (WD.GT.WSS) GO TO 13
   GO TO 21

9  AS1=COS(LAT)/(SIN(GAMMA)*TAN(S))
   AS2=SIN(LAT)/TAN(GAMMA)
   ASR=AS1+AS2
   BS1=COS(LAT)/TAN(GAMMA)
   BS2=SIN(LAT)/(SIN(GAMMA)*TAN(S))
   BSR=TAN(DELTA)*(BS1-BS2)
   ABSQT=SQRT((ASR*ASR)-(BSR*BSR)+1.)
   WSM=ACOS(((ASR*BSR)+ABSQT)/(ASR*ASR+1.))
   WSO=ACOS(((ASR*BSR)-ABSQT)/(ASR*ASR+1.))
   WSR=-WSO
   WSS=WSM
   IF (WD.LT.WSR) GO TO 13
   IF (WD.GT.WSS) GO TO 13
   GO TO 21

8  WA=ABS(WD)
   IF (WA.GT.WS) GO TO 13
   W=WD

21 A1=SIN(DELTA)*SIN(LAT)*COS(S)
   A2=SIN(DELTA)*COS(LAT)*SIN(S)*COS(GAMMA)
   A3=COS(DELTA)*COS(LAT)*COS(S)*COS(W)
   A4=COS(DELTA)*SIN(LAT)*SIN(S)*COS(GAMMA)*COS(W)
   A5=COS(DELTA)*SIN(LAT)*SIN(GAMMA)*SIN(W)

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A6=A1-A2+A3+A4+A5
THETAR=ACOS(A6)
THETAT=THETAR*PI/180
WRITE(6,1035)THETAT
IF(THETAT.GT.85.) GO TO 13
THETR=ACOS(COS(LAT)*COS(DELTA)*COS(W)+SIN(DELTA)*SIN(LAT))
THETAZ=THETR*PI/180
WRITE(6,1040)THETAZ
RB=COS(THETAR)/COS(THETR)
C FIND THE MONTHLY AVERAGE RATIO OF TOTAL RADIATION ON A TILTED SURFACE TO
C TOTAL RADIATION ON A HORIZONTAL SURFACE (RAVS)
RD=(PI/24.)*(COS(W)-COS(WS))/(SIN(WS)-(WS)*COS(WS)))
WH=WS-.1047
RT=(PI/24.)*((COS(W)-COS(WH))/(SIN(WH)-(WH)*COS(WH)))
C=CP/100.
RHOG=(.2*(1.-C))+(.7*C)
WRITE(6,1045)RHOG
RA=(RD/RT)*DAVG/HAVG
RAVG=((1.-RA)*RB)+(.5*(1.+COS(S))*RA)+.5*(1.-COS(S))*RHOG
C FIND THE MONTHLY AVERAGE INSTANTANEOUS TOTAL RADIATION ON A TILTED
C SURFACE (ITT)
ITT=RAVG*RT*HAVG
IF(ITT.GE.0.0) GO TO 12
ITT=0.0
GO TO 13
12 CONTINUE
WRITE(6,1050)
WRITE(6,1055)ITT
C SECOND, FIND THE AMOUNT OF RADIATION UTILIZED BY THE COLLECTOR SYSTEM
C FIND THE TRANSMITTANCE (TAUI) OF THE COVERS, ACCOUNTING FOR REFLECTION
C (TAURI) AND FOR ABSORPTANCE (TAUAI)
IF(THETAR.GT.0.0) GO TO 15
THETAC=0.0
GO TO 20
15 THETAC=ASIN((SIN(THETAR))/ETAC)
THETC=THETAC*PI/180

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20 CONTINUE
   IF (THETAR.GT.0.) GO TO 25
   RHOC= ((ETAC-1.)/(ETAC+1.))**2
   TAURI=(1.-RHOC)/(1.+((2.*CN)-1.)*RHOC))
   GO TO 30

25 TCR=ABS(THETAC-THETAR)
   TCC=TTHETAC+THETAR
   RH01= (SIN(TCR)/SIN(TCC))**2
   RH02= (TAN(TCR)/TAN(TCC))**2
   TA1=(1.-RH01)/(1.+((2.*CN-1.)*RH01))
   TA2=(1.-RH02)/(1.+((2.*CN-1.)*RH02))
   TAURI=(TA1+TA2)/2.
   TAUAI=EXP(-(CN*EC*THC)/COS(THETAC))
   TAUI=TAURI*TAUAI
   WRITE(6,1065) TAUI
C FIND THE EFFECTIVE TRANSMITTANCE-ABSORPTANCE PRODUCT (TAUAA)
CTHET=(COS(THETAR))**.15
ALPHA=ALPHAN*CTHET
DD=CN-2.
IF (DD) 35,40,45
35 RHOD=.16
   GO TO 50
40 RHOD=.24
   GO TO 50
45 RHOD=.29
50 CONTINUE
   TAUAA=(TAUI*ALPHA)/(1.-((1.-ALPHA)*RHOD))
   IF (DD) 55,60,65
55 B1=.27
   B2=0.0
   B3=0.0
   GO TO 70
60 B1=.15
   B2=.62
   B3=0.0
   GO TO 70

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65      B1=.14
      B2=.15
      B3=.75
70      CONTINUE
      IF (THETA*GT.3.) GO TO 42
      T1=((1.-RHOC)/(1.+RHOC))*EXP((-EC*THC)/COS(THETAC))
      T2=((1.-RHOC)/(1.+3.*FHOC))*EXP((-2.*EC*THC)/COS(THETAC))
      GO TO 43
42      RH01=(SIN(TCR)/SIN(TCC))*2
      RH02=(TAN(TCR)/TAN(TCC))*2
      T11=(1.-RH01)/(1.+RH01)
      T12=(1.-RH02)/(1.+RH02)
      TR1=(T11+T12)/2.
      T1=TR1*EXP((-EC*THC)/COS(THETAC))
      T21=(1.-RH01)/(1.+3.*RH01)
      T22=(1.-RH02)/(1.+3.*RH02)
      TR2=(T21+T22)/2.
      T2=TR2*EXP((-2.*EC*THC)/COS(THETAC))
      TAUAM=TAUA+(1.-TAUAI)*(B1+(B2*T1)+(93*T2))
      SF=(CN/48.)*TAN(THET*CR)
      WRITE(6,1070)SF
      TAUAA=.98*(1.-DF)*(1.-SF)*TAUAM
      WRITE(6,1075)TAUAA
      C FIND THE RATIO OF CRITICAL RADIATION TO MONTHLY AVERAGE INSTANT TOTAL
      C TOTAL RADIATION (RCRIT) AND THEN INTEGRATE THE AREA UNDER THE KT CURVE
      C TO FIND THE UTILIZABILITY
      RCRIT=(U*(T3-TAMB))/(TAUAA*ITT)
      WRITE(6,1080)
      WRITE(6,1085)RCRIT
      TNI=1./INT
      K=C
      E=C.0
      DO 75 M=1,INTV,1
      KT=DKT(M)
      IF (KT*GT.0.75) GO TO 80
      DH=(2.32*KT-3.22)*KT*KT+1.

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002100
002110

002150

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80      GO TO 85
85      DH=.17
        CONTINUE
        RZ=RD/RT
        G=.5*(1.-COS(S))*RHO*G
        R=(1.-(RZ*DH))*RB+(.5*(1.+COS(S))*RZ*DH)+G
        ITIT=(R/RAVG)*KT/KTAVG
        AVG(K)=ITIT
        IF(K.EQ.0) GO TO 91
        IF(K.EQ.INT) GO TO 91
        UT(K)=(AVG(K)-RCRIT)*TNI
        GO TO 92
91      UT(K)=(AVG(K)-RCRIT)*TNI/2.
92      CONTINUE
        IF(UT(K).GT.0.) GO TC 90
        UT(K)=0.0
        CONTINUE
        K=K+1
        E=E+TNI
75      CONTINUE
        UTIL=0.0
        DO 95 M=1,INTV,1
        L=M-1
        UTIL=UTIL+UT(L)
95      CONTINUE
        WRITE(6,1105)UTIL
        C FIND THE ENERGY TRANSFERRED TO STORAGE (QAVG)
        G=FLOWC/AC
        FRPRIME=FR/(1.+(FR*U)/(G*CPC))*((1./EFF)-1.))
        QAVG=AC*FRPRIME*TAVA*ITT*UTIL
        WRITE(6,1120)QAVG
        GO TO 14
13      OAVG=0.0
        WRITE(6,1110)
14      CONTINUE
        C THIRD, FIND THE AMOUNT OF ENERGY TRANSFERRED TO STORAGE.

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      HLOAD=FLOW(I)*DAYFLOW*CPS*(T3-TIN)*3.336
      IF (PROG.EQ.1.) GO TO 16
      IF (PROG.EQ.2.) GO TO 17
      IF (PROG.EQ.3.) GO TO 19
      GO TO 18
C  SYSTEM 1 IS A SIMPLE WATER HEATING SYSTEM WITH NO BACKUP HEAT
16  T4=T3+(QAVG-UAST*(T3-TROOM))/MASS
      T3=T4
      GO TO 41
C  SYSTEM 2 IS A WATER HEATING SYSTEM WITH A CONVENTIONAL WATER HEATER THAT
C  DRAWS ITS SUPPLY FROM A SOLAR HEATED STORAGE TANK
17  T4=T3+(QAVG-HLOAD-(UAST*(T3-TROOM)))/MASS
      T5=(T3+T4)/2.
      T3=T4
      Q AUX=FLOW(I)*DAYFLOW*CPS*(140.-T5)*3.336
      IF (Q AUX.GT.0.) GO TO 41
      Q AUX=0.0
      GO TO 41
80
C  SYSTEM 3 IS LIKE SYSTEM 2 EXCEPT THAT AN ANTI-FREEZE TYPE SOLUTION IS
C  USED AS THE COLLECTOR FLUID
19  T4=T3+(QAVG-HLOAD-(UAST*(T3-TROOM)))/MASS
      T5=(T3+T4)/2.
      T3=T4
      Q AUX=FLOW(I)*DAYFLOW*CPS*(140.-T5)*3.336
      IF (Q AUX.GT.0.) GO TO 41
      Q AUX=0.0
      WRITE (6,1115) T4
      CONTINUE
      WD=WD+.2618
      QSUM=QSUM+Q AUX
      WRITE (6,1310) Q AUX
      QBU=QBU+Q AUX
      CONTINUE
1  WRITE (6,1315) QBU
2  CONTINUE
      QTOT=QSUM*DAYMON

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WRITE(6,1295) QTOT
MFLOW=DAYFLOW*DAYMON
WRITE(6,1305) MFLOW
BMFLCW=MFLOW*8.336*(140.-TIN)
WRITE(6,1325) BMFLOW
QBUM=QBUM*DAYMON
WRITE(6,1320) QBUM
YQTOT=YQTOT+QTOT
YBUQ=YBUQ+QBUM
YFLOW=YFLOW+BMFLOW
UQTOT=YFLOW-YBUQ
WRITE(6,1340) YFLOW
WRITE(6,1335) YQTOT
WRITE(6,1330) YBUN
WRITE(6,1350) UQTOT
CONTINUE
3 C FOURTH, DO A COST ANALYSIS TO DETERMINE THE ECONOMIC FEASIBILITY
8 C THE COST ANALYSIS IS A LIFE CYCLE COST ANALYSIS PROGRAM
READ*,AMIR
IF(EOF(5,INPUT)).NE.0.) GO TO 99
WRITE(6,2000) AMIR
READ*,YRMORT
WRITE(6,2005) YRMORT
READ*,DNPMT
WRITE(6,2010) DNPMT
READ*,BUFCOST
WRITE(6,2015) BUFCOST
READ*,CONFCST
WRITE(6,2020) CONFCST
READ*,BUEFF
WRITE(6,2025) BUEFF
READ*,CONEFF
WRITE(6,2030) CONEFF
READ*,TAXRT
WRITE(6,2035) TAXRT
READ*,TAXBRKT

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READ*,GENINF
WRITE(6,2050) GENINF
READ*,FLINF
WRITE(6,2055) FLINF
READ*,DISCRT
WRITE(6,2060) DISCRT
READ*,ANALTRM
WRITE(6,2065) ANALTRM
YR1FL=(YFLOW/(10.**6)).*(CONF CST/30NEFF)
WRITE(6,2070) YR1FL
READ*,AREACST
WRITE(6,2120) AREACST
READ*,ARINCST
WRITE(6,2125) ARINCST
C THE INFLATION-DISCOUNT FACTOR IS USED TO REDUCE COSTS TO PERSENT YEAR COSTS
CALL DI(ANALTRM,FLINF,DISCRT,AA)
CALL DI(ANALTRM,GENINF,DISCRT,BB)
IF(YRMORT.GT.ANALTRM) GO TO 115
CALL DI(YRMORT,AMIR,DISCRT,CC)
CALL DI(YRMORT,0.0,DISCRT,FF)
GO TO 116
115 CALL DI(ANALTRM,AMIR,DISCRT,CC)
CALL DI(ANALTRM,0.0,DISCRT,FF)
CONTINUE
CALL DI(YRMORT,0.0,AMIR,EE)
WRITE(6,3030) AA
WRITE(6,3005) BB
WRITE(6,3010) CC
WRITE(6,3015) EE
WRITE(6,3020) FF
GG=FF/EE
WRITE(6,2080) GG
HH=GG+(CC*(AMIR-(1./EE)))

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WRITE(6,2085) HH
II=ONPMT+((1.-ONPMT)*(GG-(HH*TAX3RKT)))
WRITE(6,2090) II
JJ=(XTRINS*88)
WRITE(6,2095) JJ
KK=TAXRT*88*(1.-TAX8FKT)
OO=II+JJ+KK
WRITE(6,2100) KK
WRITE(6,2115) OO
R2= UQTOT/YFLCW
R3=(AREACST*AC)*ARINCST
R4=YFLCW*(1.-R2)*BUF COST/(BUEFF*(10.**6))
R5=(YR1FL-R4)*AA
R6=OO*R3
R8=R5-R6
WRITE(6,2160) R2
WRITE(6,2130) R3
WRITE(6,2135) R4
WRITE(6,2140) R5
WRITE(6,2145) R6
WRITE(6,2150) R8
CONTINUE
99
1000 FORMAT("1 DAY OF YEAR",9X,F5.0)
1005 FORMAT(" DECLINATION (DEGREES)",10X,F8.4)
1010 FORMAT(" EXTRATERRESTRIAL RADIATION ON A HORIZ SURFACE",15X,F9.4)
1015 FORMAT("0 SUNSET HOUR ANGLE (DEGREES)",33X,F8.4)
1020 FORMAT(" LONGTERM CLEARNESS INDEX ",37X,F5.4)
1025 FORMAT(" MONTHLY AVERAGE DIFFUSE RADIATION ON A ")
1030 FORMAT(" HORIZONTAL SURFACE ",42X,F8.4)
1035 FORMAT("0 ANGLE BETWEEN SUN AND COLLECTOR NORMAL",22X,F8.4)
1040 FORMAT(" SOLAR ZENITH ANGLE ",42X,F8.4)
1045 FORMAT(" GROUND REFLECTANCE ",44X,F5.4)
1050 FORMAT(" MONTHLY AVERAGE INSTANTANEOUS TOTAL RADIATION")
1055 FORMAT(" ON A TILTED SURFACE ",41X,F5.4)
1065 FORMAT(" TOTAL TRANSMITTANCE",44X,F5.4)
1070 FORMAT(" SHADING FACTOR",49X,F6.4)
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AD-A079 906

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCH00--ETC F/G 10/2
COMPUTER SIMULATION OF A SOLAR ENERGY SYSTEM WHICH UTILIZES FLA--ETC(U)
DEC 79 3 E PRINS
AFIT/GAE/AA/700-15

UNCLASSIFIED

NL

ETC
ALL
ADDITIONAL



END
DATE
FILMED
2-80
DRC

1075	FORMAT(" EFFECTIVE TRANSMITTANCE-ABSORPTANCE PRODUCT",20X,F6.4)	002870
1080	FORMAT("RATIO OF CRITICAL RADIATION TO MONTHLY AVERAGE INSTANT")	
1085	FORMAT(" TOTAL RADIATION ON A TILTED SURFACE",27X,F7.4)	002890
1090	FORMAT("0	
1105	FORMAT(" UTILIZABILITY",50X,F6.4)	002930
1110	FORMAT("NO HEAT GAIN THIS HOUR")	
1115	FORMAT(" TEMPERATURE OF FLUID IN STORAGE TANK(DEG F)",17X,F6.1)	002950
1120	FORMAT(" HEAT TRANSFER THIS HOUR(BTU/HR)",26X,F9.1)	002960
1125	FORMAT("LATITUDE(DEGREES)",44X,F5.1)	002970
1130	FORMAT(" AVERAGE AMBIENT TEMPERATURE(DEG F)",27X,F5.1)	002980
1135	FORMAT("AVERAGE DAILY RADIATION ON A HORIZONTAL")	002990
1140	FORMAT(" SURFACE (BTU/HR-SQ FT)",37X,F7.1)	003000
1145	FORMAT(" DIRT FACTOR",52X,F4.2)	003010
1150	FORMAT("PERCENT OF TIME THE GROUND IS COVERED WITH")	003020
1155	FORMAT(" MORE THAN ONE INCH OF SNOW",35X,F4.0)	003030
1160	FORMAT(" SLOPE OF COLLECTOR (DEGREES)",34X,F4.1)	003140
1165	FORMAT(" NUMBER OF COVERS ON COLLECTOR",34X,F2.0)	003050
1170	FORMAT("COLLECTOR AZIMUTH ANGLE (DEGREES)",20X,F5.1)	003060
1175	FORMAT(" SURFACE AREA OF COLLECTOR FACE (SQ FT)",22X,F6.1)	003070
1180	FORMAT(" THICKNESS OF ONE LAYER OF COVER MATERIAL",23X,F5.3)	003080
1185	FORMAT("EXTINCTION COEFFICIENT OF COVER MATERIAL",23X,F5.3)	003090
1190	FORMAT(" INDEX OF REFRACTION OF COVER MATERIAL",26X,F5.3)	003100
1195	FORMAT(" ABSORPTIVITY OF COLLECTOR",38X,F4.2)	003110
1200	FORMAT("HEAT REMOVAL EFFICIENCY OF COLLECTOR",27X,F4.2)	003120
1205	FORMAT(" COLLECTOR HEAT LOSS COEFFICIENT",32X,F4.2)	003130
1210	FORMAT(" MASS FLOW RATE OF FLUID THROUGH COLLECTOR IN")	003140
1215	FORMAT(" POUNDS-PER-HOUR",45X,F6.1)	003150
1220	FORMAT("COEFF OF SPECIFIC HEAT OF COLLECTOR FLUID",22X,F4.2)	003160
1225	FORMAT(" NUMBER OF INTERVALS DESIRED ON F-CHART",24X,I2)	003170
1230	FORMAT(" INITIAL TEMPERATURE OF FLUID IN STORAGE TANK",17X,F5.1)	003180
1235	FORMAT(" INITIAL TEMPERATURE INSIDE BUILDING",26X,F5.1)	003190
1240	FORMAT(" EFFICIENCY OF HEAT EXCHANGER",35X,F4.2)	003200
1245	FORMAT(" TYPE OF SYSTEM IN USE",1X,I3.0)	003210
1250	FORMAT("AMOUNT OF FLUID IN STORAGE TANK (GAL)",24X,F7.1)	003220
1255	FORMAT(" SURFACE AREA OF STORAGE TANK (SQ FT)",25X,F5.1)	
1260	FORMAT(" INSULATION THICKNESS ON STORAGE TANK (IN)",20X,F4.2)	003240

1255	FORMAT("0 CONDUCTIVITY OF STORAGE TANK INSULATION",24X,F4.2)	003250
1270	FORMAT(" COEFFICIENT OF SPECIFIC HEAT OF STORAGE FLUID",18X,F4.2)	003260
1275	FORMAT(" NUMBER OF DAYS PROGRAM IS TO RUN",30X,I2)	003270
1280	FORMAT(" KT(",12,") = ",F6.4)	
1290	FORMAT("0 NUMBER OF DAYS IN THE MONTH",38X,F4.0)	
1295	FORMAT("0 TOTAL USEFUL SOLAR ENERGY FOR MONTH",24X,F10.1)	
1330	FORMAT(" AVERAGE DAILY FLOW USED (GAL)",31X,F10.1)	
1305	FORMAT(" MONTHLY FLOW USED (GAL)",35X,F11.1)	
1310	FORMAT(" BACKUP HEAT USED THIS HOUR(BTU)",27X,F10.1)	
1315	FORMAT(" DAILY BACKUP HEAT USED(3TU)",31X,F10.1)	
1320	FORMAT(" MONTHLY BACKUP HEAT USED (3TU)",28X,F11.1)	
1325	FORMAT(" MONTHLY LOAD USED (BTU)",35X,F11.1)	
1330	FORMAT(" YEARLY BACKUP ENERGY USED (9TU)",25X,F13.1)	
1335	FORMAT(" YEARLY SOLAR ENERGY USED (9TU)",26X,F13.1)	
1340	FORMAT("0 YEARLY LOAD USED (BTU)",34X,F13.1)	
1345	FORMAT(" NUMBER OF MONTHS PROGRAM IS TO RUN",31X,I2)	
1350	FORMAT(" YEARLY SOLAR ENERGY ACCOUNTING FOR TANK LOSS",12X,F13.1)	
2000	FORMAT("0 ANNUAL MORTGAGE INTEREST RATE",36X,F4.2)	
2005	FORMAT(" TERM OF MORTGAGE",49X,F4.0)	
2110	FORMAT(" DOWN PAYMENT ,AS FRACTION OF INVESTMENT",24X,F6.4)	
2015	FORMAT(" BACKUP FURNACE COST",40X,F10.2)	
2020	FORMAT(" CONVENTIONAL FURNACE COST",34X,F10.2)	
2025	FORMAT(" EFFICIENCY OF SOLAR BACKUP FURNACE",31X,F4.2)	
2030	FORMAT(" EFFICIENCY OF CONVENTIONAL SYSTEM FURNACE",24X,F4.2)	
2035	FORMAT(" TAX RATE, FRACTION OF INVESTMENT",32X,F6.4)	
2040	FORMAT(" EFFECTIVE INCOME TAX BRACKET",36X,F5.3)	
2045	FORMAT(" EXTRA INS AND MAINT COST, FRACT OF INVESTMENT",20X,F4.2)	
2050	FORMAT(" GENERAL INFLATION RATE PER YEAR",33X,F5.3)	
2055	FORMAT(" FUEL INFLATION RATE PER YEAR",35X,F6.3)	
2060	FORMAT(" DISCOUNT RATE",51X,F5.3)	
2065	FORMAT(" TERM OF ECONOMIC ANALYSIS",40X,F4.0)	
2070	FORMAT(" FIRST YEAR NON-SOLAR FUEL EXPENSE",28X,F8.2)	
2080	FORMAT(" LOAN PAYMENT",50X,F7.2)	
2085	FORMAT(" LOAN INTEREST",46X,F10.2)	
2090	FORMAT(" CAPITAL COST",47X,F10.2)	
2095	FORMAT(" INSURANCE AND MAINTENANCE COSTS",28X,F10.2)	

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2100 FORMAT(" PROPERTY TAX",47X,F10.2)
2115 FORMAT(" RESIDENTIAL COSTS",42X,F10.2)
2120 FORMAT(" COLLECTOR AREA DEPENDENT COSTS",29X,F10.2)
2125 FORMAT(" COLLECTOR AREA INDEPENDENT COSTS",27X,F10.2)
2130 FORMAT(" INVESTMENT IN SOLAR",47X,F10.2)
2135 FORMAT(" FIRST YEAR FUEL EXPENSE",35X,F10.2)
2140 FORMAT(" FUEL SAVINGS",47X,F10.2)
2145 FORMAT(" RESIDENTIAL EXPENSES",33X,F10.2)
2150 FORMAT(" RESIDENTIAL SAVINGS",47X,F10.2)
2155 FORMAT(" TEMPERATURE OF FLUID FROM SUPPLY",32X,F5.1)
2160 FORMAT(" PERCENT OF ENERGY SUPPLIED BY SOLAR",29X,F5.3)
3000 FORMAT(" AA =",56X,F8.3)
3005 FORMAT(" BB =",56X,F8.3)
3010 FORMAT(" CC =",56X,F8.3)
3015 FORMAT(" EE =",56X,F8.3)
3020 FORMAT(" FF =",56X,F8.3)
STOP"END OF PROGRAM"
END

SUBROUTINE DI(YRS,RTINF,DISC,ZZ)
IF (RTINF.EQ.DISC) GO TO 105
ZZ=(1./(DISC-RTINF))*(1.-((1.+RTINF)/(1.+DISC))**YRS)
RETURN
105 ZZ=YRS/(1.+RTINF)
RETURN
END

```

Vita

Barry Eugene Prins was born 25 November 1945 in Holland, Michigan. He graduated from Holland High School in 1964 and the United States Air Force Academy in 1968 with the degree of Bachelor of Science in General Engineering. After commissioning he attended pilot training graduating in August 1969. He served as an HC-130 pilot at RAF Woodbridge, United Kingdom, until June 1973 and a C-130 pilot at Korat RTAFB, Thailand. He returned in May 1974 to Hill AFB, Utah, to become an instructor in the HC-130. He entered the Air Force Institute of Technology, School of Engineering in May 1978.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This thesis is a computer simulation of a solar energy system that utilizes flat-plate solar collectors. By using available data from the U.S. Weather Bureau, the location and orientation of the collector, characteristics of the collector, and the type of storage and backup heat system in use, it is possible to find the amount of solar energy collected and transferred to storage.		

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A life cycle cost analysis can be accomplished by using financial data and an inflation-discount function to reduce all costs to present year dollars. By varying any of a number of parameters the operator can determine what effect it has on the amount of energy collected and the life cycle costs. Results of running the program for a solar water heater system indicate that such a system is cost effective, when compared to a gas water heater system, only when the federal and state tax incentives were taken into account. However, electricity is approximately three times as expensive as gas per BTU of energy gained so the solar energy system is economically feasible when compared to an electric water heating system.

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